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FUEL LUBRICITY IMPACT ON SHIPBOARD ENGINE AND FUEL SYSTEMS AND SENSITIVITY OF U.S. NAVY DIESEL ENGINES TO LOW-SULFUR DIESEL FUEL

INTERIM REPORT
TFLRF No. 414

by
Douglas M. Yost

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Southwest Research Institute® (SwRI®)
San Antonio, TX

by
Allen S. Comfort
Luis A. Villahermosa

U.S. Army TARDEC
Force Projection Technologies
Warren, Michigan

Contract No. DAAE-07-99-C-L053 (WD28 & WD31)

June 2011

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UNCLASSIFIED: Distribution Statement A. Approved for public release

June 2011

Approved by:

Gary B. Bessee, Director
U.S. Army TARDEC Fuels and Lubricants
Research Facility (SwRI®)

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
30-06-2011	Interim Report	March 2007 – June 2011

4. TITLE AND SUBTITLE
Fuel Lubricity Impact on Shipboard Engine and Fuel Systems and Sensitivity of U.S. Navy Diesel Engines to Low- Sulfur Diesel Fuel

5a. CONTRACT NUMBER
DAAE07-99-C-L053

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Yost, Douglas M.

5d. PROJECT NUMBER
SwRI 08.03227.28; SwRI 08.03227.31

5e. TASK NUMBER
WD 28; WD 31

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

U.S. Army TARDEC Fuels and Lubricants Research Facility (SwRI®)
Southwest Research Institute®
P.O. Drawer 28510
San Antonio, TX 78228-0510

8. PERFORMING ORGANIZATION REPORT NUMBER
TFLRF No. 414

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

U.S. Army RDECOM
U.S. Army TARDEC
Force Projection Technologies
Warren, MI 48397-5000

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT
This project attempted to determine the kerosene and Ultra Low Sulfur Diesel fuel lubricity requirements of Delphi DPA rotary fuel injection pumps and Detroit Diesel unit injectors. A test stand was configured to operate a rotary fuel injection pump and a stand configured to operated four unit injectors simultaneously, with data acquisition and control systems for logging data. Results suggest that synthetic kerosene fuel adversely impacts rotary fuel injection pump performance and durability. Synthetic diesel fuel can be blended with petroleum diesel fuel and fuel lubricity additives to provide the same protection as F-76 diesel fuel in rotary fuel injection pumps. The unit injectors are less sensitive to the low lubricity fuels than the rotary fuel injection pumps.

15. SUBJECT TERMS
High-speed diesel; S-8; Rotary Fuel Injection Pump; Synthetic Fuel; Ultra Low Sulfur Diesel; Lubricity; Unit Injectors

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON / 19b. TELEPHONE NUMBER *(include area code)*
Unclassified	Unclassified	Unclassified	Unclassified	76	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39.18

EXECUTIVE SUMMARY

The U. S. Navy, U. S. Coast Guard and the Military Sea Lift Command rely on diesel fuel, for both main propulsion and power generation, in a large majority of their fleets. Much of the equipment is old and was put into service before diesel fuel lubricity was a significant problem. It is expected that much of the equipment will be sensitive to low-lubricity fuel and the problems it can cause, mainly premature wear of fuel-wetted components.

Two high-speed diesel engine fuel injection systems were identified that would be susceptible to low lubricity fuel effects on durability. The systems were (1) fuel-lubricated, rotary-distributor type fuel injection pumps and (2) mechanical unit injectors, with precision machined plunger helixes and sharp edges. Fuels included were: a synthetic kerosene fuel, a petroleum kerosene fuel, a F-76 diesel fuel, a commercial synthetic diesel fuel, and a reference Ultra Low Sulfur Diesel (ULSD) fuel. Corrosion Inhibitor/Lubricity Improver (CI/LI) additive effects were also included to modify fuel lubricity levels.

Operation of rotary fuel injection type pumps with synthetic kerosene fuel, whether blended, or with additives, has resulted in excessive or premature wear. That fact suggests neither the lubricity nor the viscosity of the S-8 or S-8 blends are adequate for the rotary injection pump use, with the current additives. Petroleum kerosene fuel, neat or with additives, resulted in performance degradation of the rotary fuel injection system, but not excessive premature wear. A synthetic ULSD/petroleum ULSD blend with a QPL lubricity additive offer adequate protection in the Delphi fuel lubricated rotary fuel injection equipment.

The unit injectors are less prone to wear with any of the lubricity and viscosity levels of the fuels evaluated. Migration of lubricant from the top of the injector appears to offer additional protection with low lubricity fuels.

FOREWORD/ACKNOWLEDGMENTS

The U.S. Army TARDEC Fuel and Lubricants Research Facility (TFLRF) located at Southwest Research Institute® (SwRI®), San Antonio, Texas, performed this work during the period March 2007 through June 2011 under Contract No. DAAE-07-99-C-L053. The U.S. Army Tank-Automotive RD&E Center, Force Projection Technologies, Warren, Michigan administered the project. Mr. Luis Villahermosa (AMSRD-TAR-D/MS110) served as the TARDEC contracting officer's technical representative. Ms. Sherry Williams of NAVAIR served as the project technical monitor.

The author would like to acknowledge the contributions of Messrs. Craig Springer and Rodney Grinstead of the TFLRF technical support staff along with the administrative and report-processing support provided by Ms. Dianna Barrera.

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ACRONYMS AND ABBREVIATIONS

%	Percent
°C	Degrees centigrade
@	At
ASTM	American Society for Testing and Materials
BOCLE	Ball on Cylinder Lubricity Evaluator
BTU	British thermal units
cc	Cubic centimeter
cm	Centimeter
CI/LI	Corrosion Inhibitor/Lubricity Improver
DDC	Detroit Diesel Corporation
deg	Degree
EPA	Environmental Protection Agency
HFRR	High-frequency reciprocating rig
IBP	Initial boiling point
Kg	Kilo-gram
L	Liter
Max	Maximum
Min	Minimum
ml	Milliliter
mm	Millimeter
ppm	Parts per million
psi	Pounds per square inch
QPL	Qualified Products List
RATT	Radioactive Tracer Technique
RPM	Revolutions per minute
sec	Seconds
SLBOCLE	Scuffing load ball on cylinder lubricity evaluator
SwRI	Southwest Research Institute
TFLRF	U.S. Army TARDEC Fuels and Lubricants Research Facility
ULSD	Ultra-Low Sulfur Diesel
USMC	United States Marine Corps.
USN	United States Navy
WSD	Wear Scar Diameter

1.0 OBJECTIVE

The U. S. Navy, U. S. Coast Guard and the Military Sea Lift Command rely on diesel fuel, for both main propulsion and power generation, in a large majority of their fleets. Much of the equipment is old and was put into service before diesel fuel lubricity was a significant problem. It is expected that much of the equipment will be sensitive to low-lubricity fuel and the problems it can cause, mainly premature wear of fuel-wetted components. The objective of this project is to determine the sensitivity of Navy diesel fuel injection systems to synthetic, ultra-low sulfur diesel, or aviation kerosene fuels.

2.0 BACKGROUND

As far as newer equipment is concerned, most manufacturers have taken the potential problem with fuel lubricity into consideration and are using components and materials that are less sensitive to fuel lubricity. However, some potential for problems still exists and must be addressed. Furthermore there were potential benefits identified for using JP-5 grade kerosene in lieu of marine diesel fuel for all fleet diesel engines. JP-5 grade kerosene also has potential impacts on diesel engine fuel injection system wear, due to lower lubricity and viscosity. For these reasons, the Navy undertook to investigate the extent of these potential problems and identify the equipment that is most sensitive.

3.0 APPROACH

Two high-speed diesel engine fuel injection systems were identified that would be susceptible to low lubricity fuel effects on durability. Fuel-lubricated, rotary-distributor type fuel injection pumps are known to be highly sensitive to both low lubricity and low viscosity fuels. Mechanical unit injectors, with precision machined plunger helixes and sharp edges to control injection start and duration, were thought to be susceptible to scuffing from internal wear debris. Fuels were defined that spanned a range of lubricities as determined by the ASTM D 6079 Scuffing Load

Test. The scuffing load test, which measures the load for the onset of scuffing, was felt to be more representative of the fuel lubricity requirements of diesel fuel injection pumps for protection from damaging wear. Also included were a synthetic kerosene fuel, a commercial synthetic diesel fuel, and a reference Ultra Low Sulfur Diesel (ULSD) fuel. Corrosion Inhibitor/Lubricity Improver (CI/LI) additive effects were also included to modify fuel lubricity levels.

Initial plans were to use a Radioactive Tracer Technique (RATT) on selected fuel injection pump components to evaluate fuel lubricity and fuel type effects on fuel injection pump wear in motorized fuel injection test rigs. The thought being that the RATT approach would allow shorter operating time with each fuel to identify fuel specific wear rates. Difficulties with the RATT technique eventually led to performing 500 hour fuel injection system bench tests with the various test fuels. Fuel injection test stands were configured for a Delphi DPA Rotary fuel injection pump and Detroit Diesel mechanical unit injectors.

4.0 DISCUSSION

4.1 LABORATORY LUBRICITY BENCH TESTS

SwRI is analyzing the two primary test fuels used in this project. One is an aviation kerosene fuel and one is a reference diesel fuel. They are being analyzed for the purposes of this project and are also being checked for conformance to the JP-5 and F-76 specifications, respectively. The test results completed thus far are given in Table 1.

Table 1. Navy Lubricity Hardware Test Program Test Fuels

Property	Units	F1000 S-8	F2000 Jet A	F3000 Diesel
Cetane Number, D 613			—	48
Density @ 15°C, D 4052	kg/m^3	754.8	788.5	841.9

Property	Units	F1000 S-8	F2000 Jet A	F3000 Diesel
Distillation, D 86	°C @ vol% evap. IBP 50 90	 157 202 250	 133 181 232	 171 257 306
Kinematic Viscosity @ 40°C, D 445	mm^2/s	1.28	1.09	2.36
Kinematic Viscosity @ -20°C, D 445	mm^2/s		3.23	—
Net Heat of Combustion, D 240	BTU/lb		18,679	18,365
Total Sulfur, D 5453	mass %	~0	0.004	0.035
BOCLE, D 5001	mm	1.02	0.49	N/A
HFRR, D 6079	mm	795	625	323
SLBOCLE, D6078	g	1050	1850	3800

Several fuel blends of interest were made and tested in lubricity bench tests as shown in Table 2.

Table 2. Fuel Lubricity Test Results

Lubricity Tests	Fuel Description					
	S-8	Fuel 2000	Blend (50%v S-8/50%v Fuel 2000)	Blend +9ppm DCI-4A	Blend +22ppm DCI-4A	S-8+22ppm Nalco
ASTM D 6078 HFRR, microns	795	625	615	681	703	735
ASTM D 5001 BOCLE, mm	1.00	0.49	0.53	0.54	0.54	0.57
ASTM D 6079 SLBOCLE, g	1050	1850	2150	2400	2900	1650

4.2 DELPHI ROTARY FUEL INJECTION PUMPS

4.2.1 Test No. 1: Jet A (F2000)

A 500 hour test was completed using the 2000-g scuffing load fuel with an approximate 10% reduction of the injected volumetric fuel flow rate, as measured by the endurance stand instrumentation from the start of testing. The 500 hour post-test pump calibration stand results, on an accurate stand, using calibration fluid showed a 24% delivery decrease at 1300 rpm pump speed and an erratic delivery between injectors. The 500 hour test was performed at 1300 rpm and full rack, thus the delivery impact and erratic performance was expected to be more severe at the rated condition. Fuel delivery at other speeds had not changed.

Inspections of components revealed wear scars on the roller shoes and plungers, which can impact fuel metering and delivery. Components were analyzed for alloy constituents as shown in Table 3. Cr would be the dominant tracer element if irradiated, and would have a 27.7 day half-life for radioactive decay. The Roller Shoes and Plungers are similar enough that they can be activated together and are able to calculate combined mass wear rate. The roller shoe and plungers form a wear couple as shown in Figure 1.

Table 3. Elemental Analysis of Pump Components

Alloy Element	Roller Shoe	Plunger	Roller	Stop Plate
Fe	97.36	97.77	83.71	98.67
Cr	1.49	1.56	4.14	0.29
Mn	0.51	0.34	—	0.71
P	0.29	—	—	—
Si	0.36	0.33	—	0.33
Mo	—	—	5.19	—
W	—	—	5.05	—
V	—	—	1.91	—

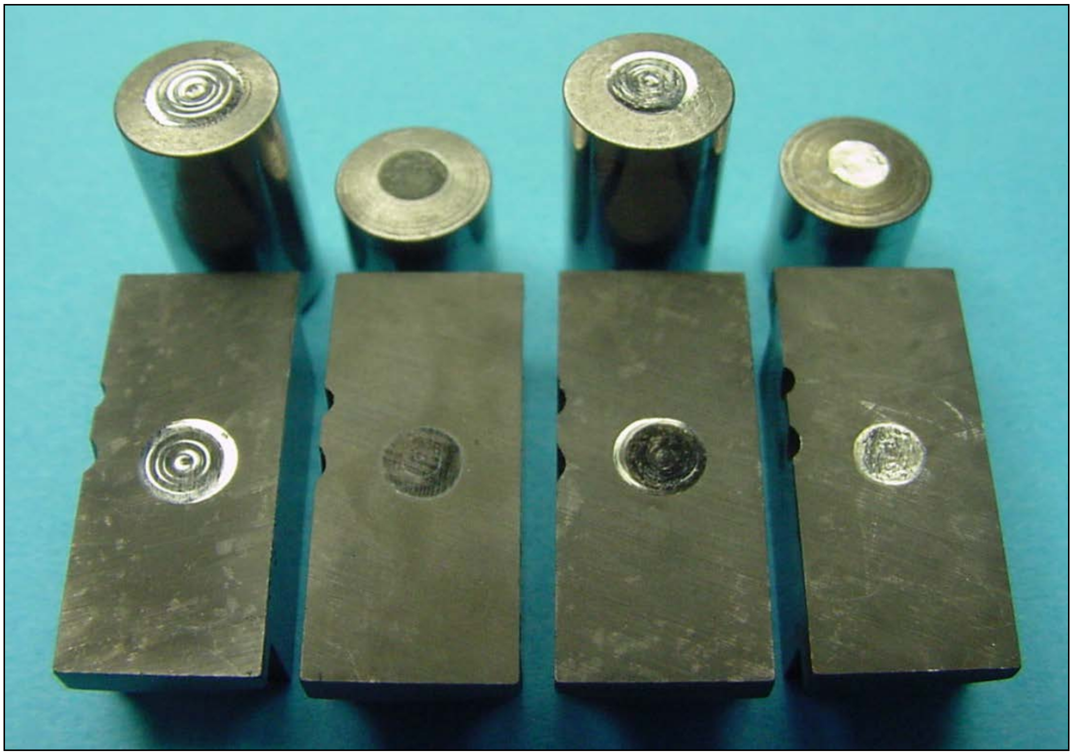

Figure 1. Rotary Pump Roller Shoes and Plungers 500 hours with 2000-g Fuel

4.2.2 Test No. 2: Neat S-8 (F1000)

A used Delphi pump was operated on the test stand. The pump was inspected and built with serviceable components, then sent to a diesel fuel injection service facility to verify pump operation. The pump was installed on the test stand to validate the test stand drive coupling arrangement and alignment. The drive system was validated by operating the pump for several hours on diesel fuel and monitoring the pump performance. Since the pump was mounted on the stand it was decided to switch load the fuel from the diesel fuel to the Neat S-8 (F1000) fuel. The pump is used on the Cummins 3.9L “B” series engine that has the following military applications: USMC rough terrain crane, USN 4000 lb rough terrain forklift, and Army 7.5T wheeled crane. The pump stand was operated at rated speed on neat S-8 fuel, at 16.5 hours the pump had worn to the point where there was no fuel delivery. Inspection of the pump revealed extreme roller and cam wear. Figure 2 shows the wear debris in the pump. There were indications of severe fuel lubricity problems with using neat S-8 fuel in a fuel lubricated rotary injection pump.

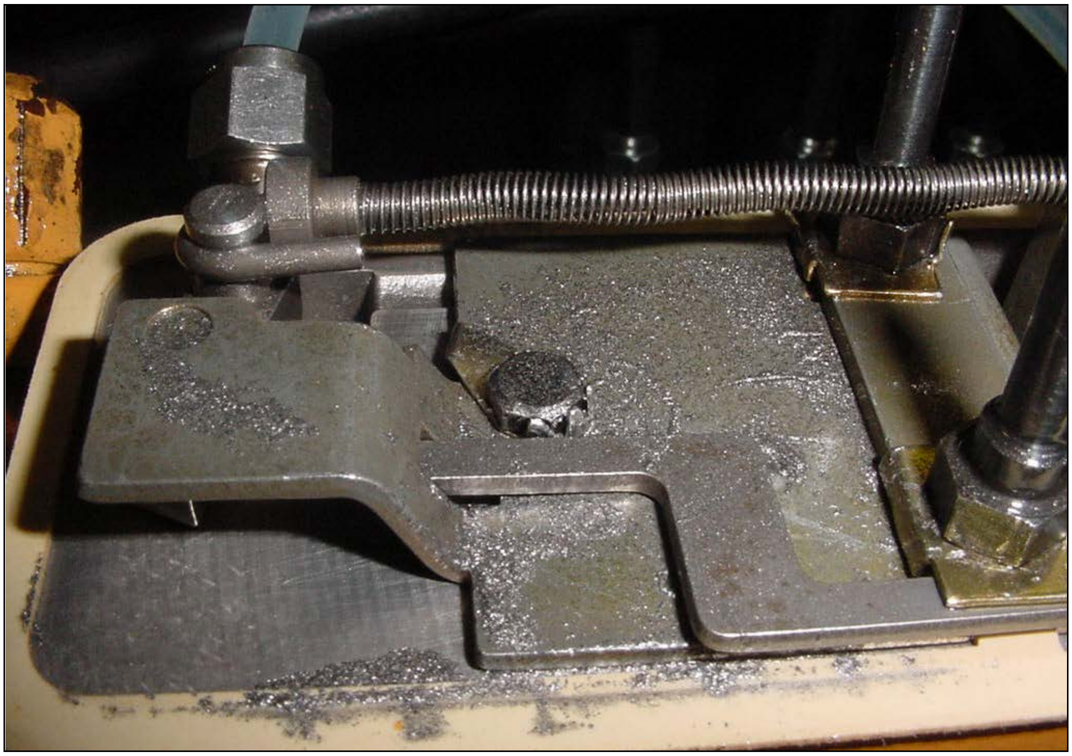

Figure 2. Delphi Pump Wear Debris with S-8 (F1000) Fuel

4.2.3 Test No. 3: S-8 + 22.5-ppm DCI-4A

The Cummins 6BT5.9M engine that powers USN Rigid Inflatable Boats utilizes the Delphi CAV DPA rotary injection pump. Test 3, scheduled for 500 hours, was started using S-8 treated with DCI-4A at the maximum recommended treat level of 22.5 ppm as defined by QPL-25017. The test was stopped at 365 hours because of reduced fuel flow and increasing fuel return temperature. Table 4 shows the flow performance for the pump when new, after a 2 hour run in, after the 250 hour check, and at the end of the test (365 hours). At the end of test, the delivery at 1300 rpm was down, the delivery at 1200 rpm had fallen, but more importantly the governor action was compromised, that could lead to engine over speed. Governor action is compromised due to the accumulated wear on the governor linkages, arms, and pivots. Increased fuel return temperatures are a result of the increased level wear on the internal pump components.

Table 4. Delphi DPA Rotary Pump with S-8 + 22.5 ppm DCI-4A

Model Number: 3062F304			Serial Number: 11589CYG			
Test Operation	**RPM**	**Range**	**Results, Flow in cc/1000 Strokes except where noted**			
Date			8/6/2005	6/21/2006	7/24/2006	8/7/2006
Comments			new	run-in	test drum 1	test drum 2
Hours			0	2	250	365
Test Fluid			Cal. Fluid	Cal. Fluid	S-8+ DCI-4A	S-8+ DCI-4A
Transfer Pressure	1200	77 to 92 psi	91	92	90	90
Fuel Delivery	1200	110 cc ± 1.1 Max. Spread 11.0	109	109	109	**99***
Housing Pressure	1200	No Spec.	0	0	0	0
Fuel Delivery (Gov.)	1430	2 cc Max.	0	0	**7.9**	**29.2**
Transfer Pressure	100	10 psi Min.	8.5	10	10	10
Advance	150	0.5 deg.	0	0	0	0
Advance	300	5.75 to 6.25 deg.	6	6	6	6
Cranking Fuel Delivery	100	90 cc	96	96	97	99
Fuel Return	1200	10 to 110 cc/100 Strokes	41	55	43.5	44
Idle	300	3cc (No Spec.)	15	5	**32.5**	**33.5**
Complete Breakaway	1445	No Spec.	0	0	**5.3**	**26.5**
Shutoff Lever & Solenoid	200	0.8 cc max	0	0	0.5	0.5
Idle Governor	325	No Spec.	2	12	18	80
Record Fuel Delivery	1300	1200 RPM del. -4cc	105	105	**70.7**	**44.5**
Transfer Pressure	1300	No Spec.	94	97	97	100
Transfer Pressure	1430	No Spec.	115	126	112	107
Fuel Delivery[#]	1430	2 cc Max.	0	0	**6.6**	**27.7**
Fuel Delivery	1277	No Spec.	N.R.	N.R.	75	48
Fuel Delivery	1400	No Spec.	N.R.	N.R.	35.3	38.8

*Bold parameters are of concern

[#]Fuel Delivery checked again at 1430-RPM after Complete Breakaway to determine if governor properly resets

4.2.4 Test No. 4: Fuel Blend + 9 ppm DCI-4A

A test of the 50/50 S-8/Jet A fuel with 9 ppm DCI-4A was evaluated for a Delphi rotary pump. The pump was run-in for 2 hours at the fuel injection service, however there was damage due to un-lubricated contact between the drive thrust washer and the aluminum housing. The service supplied a new housing and installed the internal components into the new housing, made adjustments, and performed a calibration check noted as New housing in Table 5. At 153 hours, the test was stopped because of apparent pump wear. As shown in Figure 3, fuel temperature was increasing (the middle plot), and pump flow was decreasing (bottom plot). The pump cover was removed and metal wear debris was present, Figure 4. The pump-metering valve felt as if there was debris in the bore.

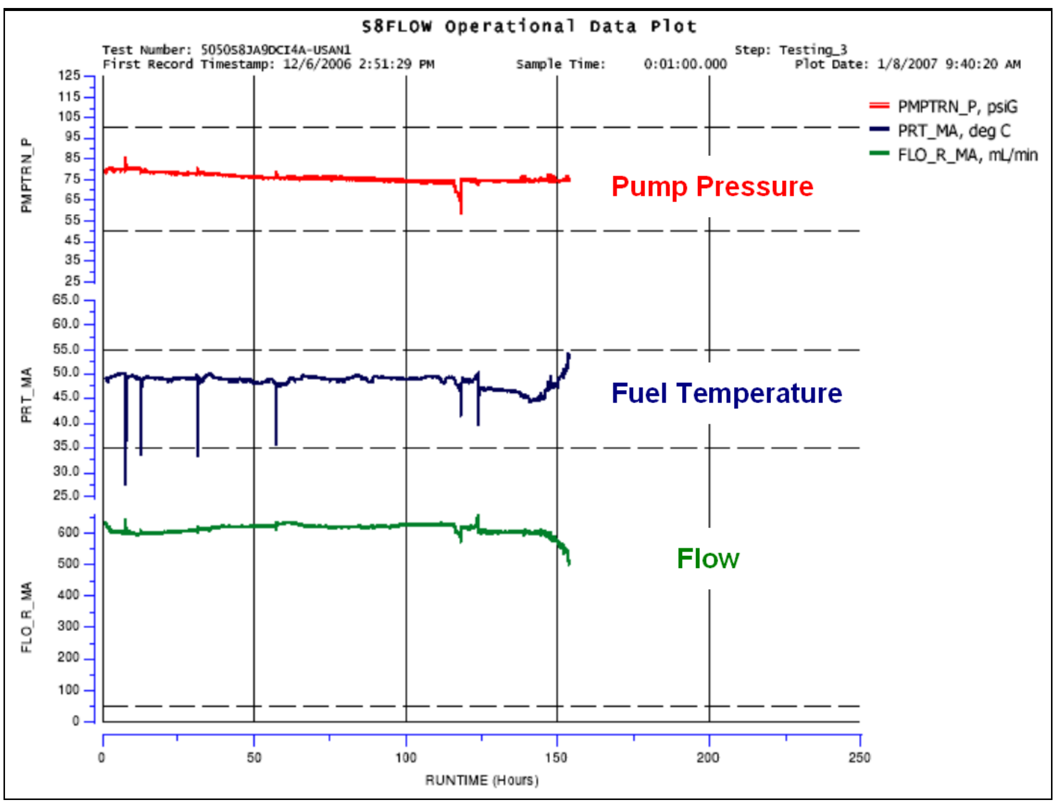

Figure 3. Operational Data Plot

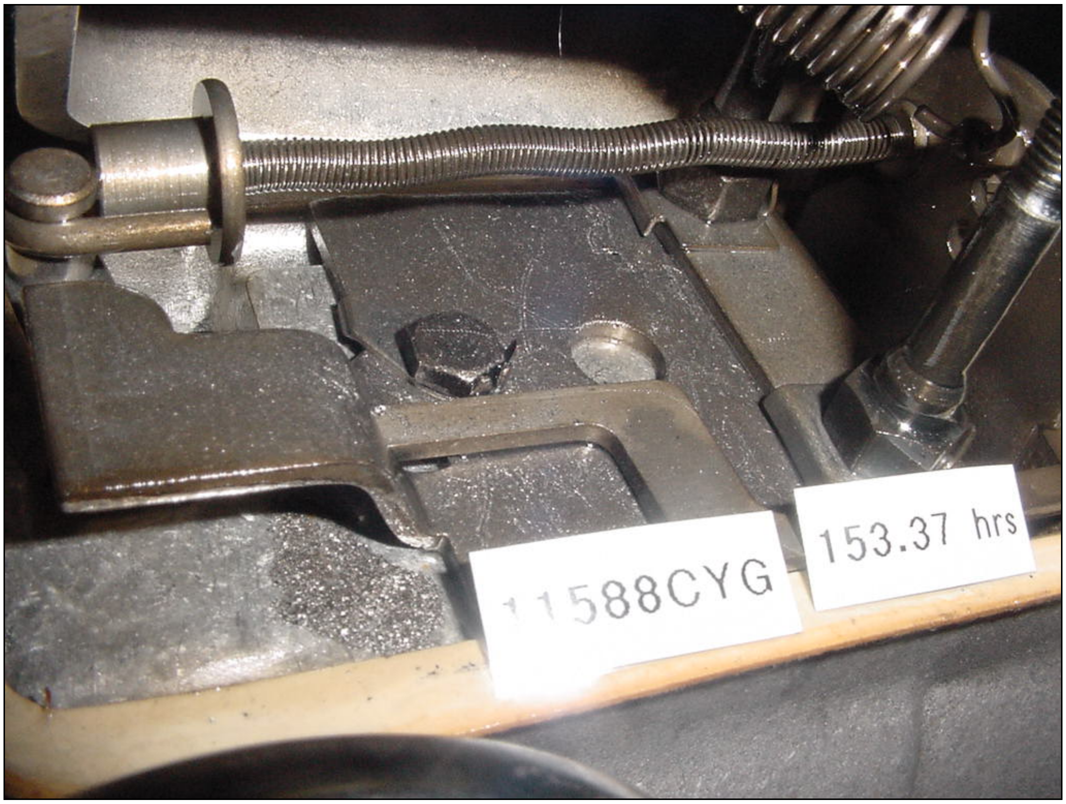

Figure 4. Metal Debris inside Pump at 153-hours for Test No. 4

The pump flow performance presented in Table 5 was most impacted at cranking fuel delivery conditions with low flow. Fuel delivery was also low at 1200 and 1300 rpm pump speed, and delivery was excessive at governor breakaway.

4.2.5 Test No. 5: Fuel Blend + 22.5-ppm DCI-4A

A test of the 50/50 S-8/Jet A fuel with 22.5 ppm DCI-4A was performed for a Delphi rotary pump. Noted in Figure 5 is a change in pump return temperature and delivery at around 39 hours of operation. The change in return temperature suggests a change in the wear rate of the components in the pump. Likewise the variability of the pump delivery suggests a change in the pump, however the pump was still delivering fuel above the flow limit at 39 hours.

Table 5. Delphi DPA Rotary Pump, Test 4

Model Number: 3062F304			**Serial Number: 11588CYG**			
Test Operation	**RPM**	**Range**	**Results, Flow in cc/1000 Strokes except where noted**			
Comments			new	run-in	New Housing	EOT
Hours			0	2	0	153.4
Test Fluid			Cal. Fluid	Cal. Fluid	Blend + 9 ppm CI	Blend + 9 ppm CI
Transfer Pressure	1200	77 to 92 psi	91	90	89	79
Fuel Delivery	1200	110 cc ± 1.1 Max. Spread 11.0	113	113	120	**105***
Housing Pressure	1200	No Spec.	0	0	0	0
Fuel Delivery (Gov.)	1430	2 cc Max.	2.1	2	2	7
Transfer Pressure	100	10 psi Min.	12	12	11	15
Advance	150	0.5 deg.	0.5	0.5	0.5	0.5
Advance	300	5.75 to 6.25 deg.	5.75	5.75	5.75	5.75
Cranking Fuel Delivery	100	90 cc	103	102	106	**70**
Fuel Return	1200	10 to 110 cc/100 Strokes	40	41	45	40
Idle	300	3cc (No Spec.)	3.1	3	3.1	3
Complete Breakaway	1445	No Spec.	0.5	1.5	1	**5**
Shutoff Lever & Solenoid	200	0.8 cc max	0.5	0.5	0.5	0.5
Idle Governor	325	No Spec.	1.5	1.5	1.5	0.5
Record Fuel Delivery	1300	1200 RPM del. -4cc	113	113	120	**95**
Transfer Pressure	1300	No Spec.	94	92	91	81
Transfer Pressure	1430	No Spec.	112	111	112	105
Fuel Delivery	1430	2 cc Max.	2	4.1	2	**6**

*Bold parameters are of concern

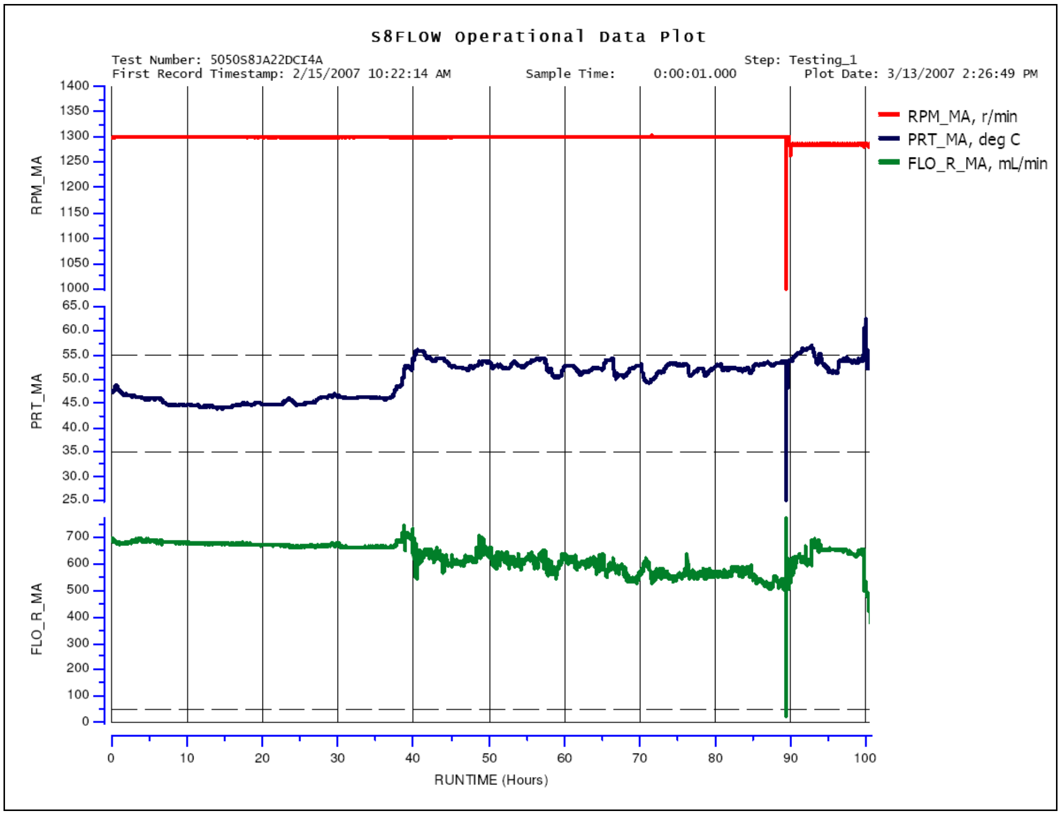

Figure 5. Delphi DPA Pump Performance Data with a 50/50 Blend of S-8/Jet A with 22.5 ppm DCI-4A Corrosion Inhibitor/Lubricity Improver (CI/LI) Additive

At 100 hours the stand shut down with a low flow rate, removal of the top cover indicated wear debris from the pump. Inspection of the hydraulic head and cam revealed massive wear between the rollers, roller shoes, and cam lobes. Figure 6 is a picture showing the heavy wear on the cam lobes. The wear pattern suggests the rollers were both sliding and rolling with evidence of material transfer.

The cam roller from the DPA pump is shown in Figure 7. The wear seen on the roller in Figure 7 is typical for all four rollers. Not evident from the photograph, the roller is slightly tapered due to wear. Once the roller becomes tapered, wear in the pump would have accelerated because the roller would no longer roll on an axis parallel to the driveshaft axis of rotation. Figure 8 shows one of the roller shoes, with severe wear that suggest the roller was shifting in the shoe, and not just rotating. The level of wear debris evident throughout the pump is shown on the governor weight in Figure 9.

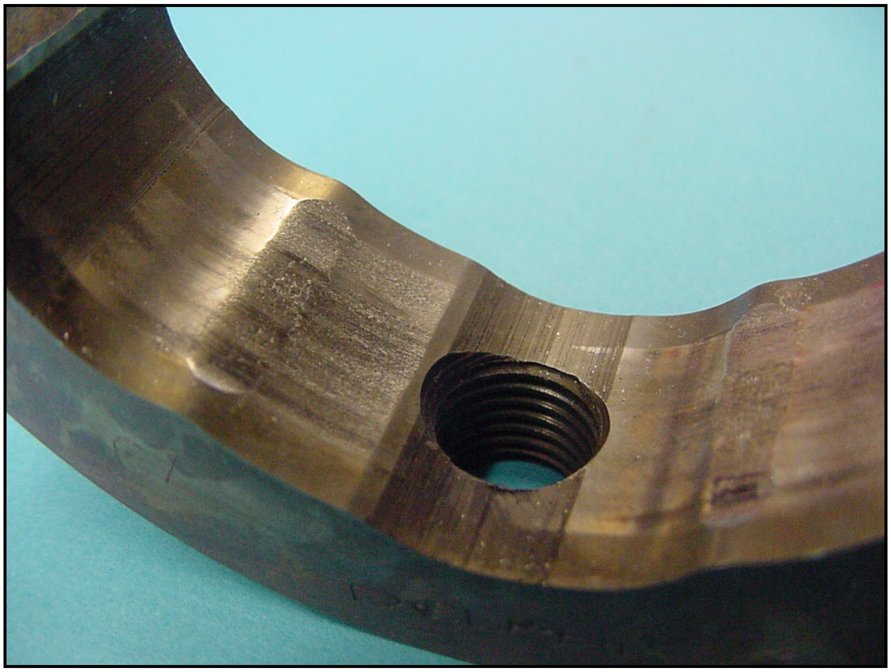

Figure 6. Delphi DPA Pump Cam Lobe Wear with 50/50 S-8/Jet A Fuel with 22.5 ppm DCI-4A CI/LI Additive

Figure 7. Delphi DPA Pump Cam Roller Wear with 50/50 S-8/Jet A Fuel with 22.5-ppm DCI-4A CI/LI Additive

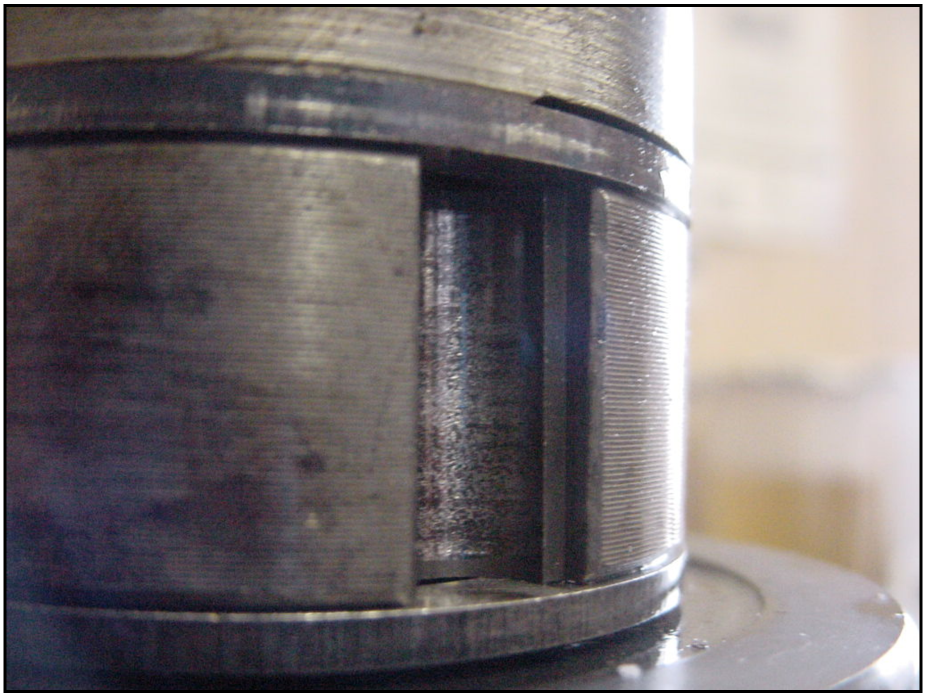

Figure 8. Delphi DPA Pump Cam Roller Shoe Wear with 50/50 S-8/Jet A Fuel with 22.5-ppm DCI-4A CI/LI Additive

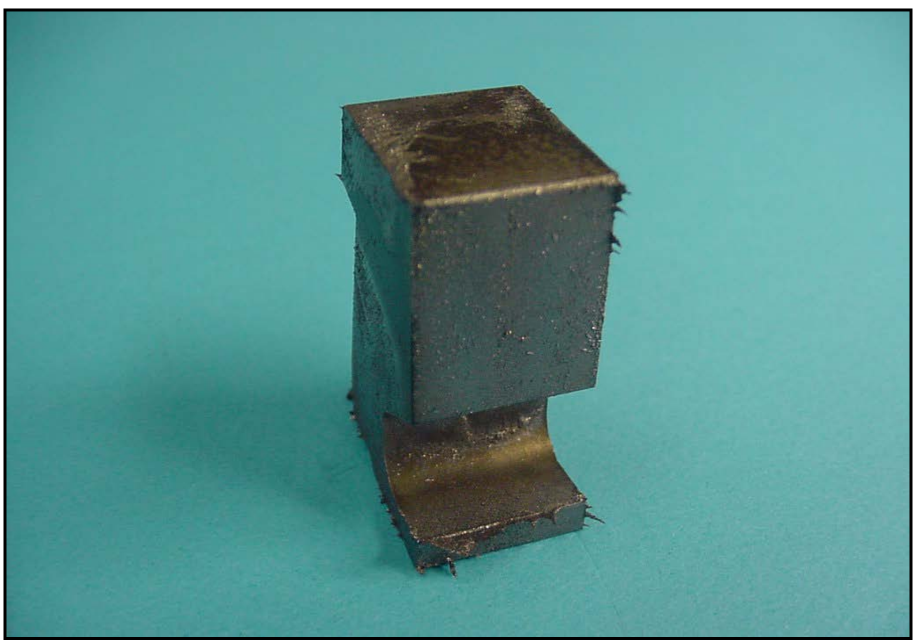

Figure 9. Delphi DPA Pump Governor Weight with 50/50 S-8/Jet A Fuel with 22.5-ppm DCI-4A CI/LI Additive

To determine if the Delphi cam and roller components for the S-8 tests were manufactured to the same Rockwell "C" hardness, measurements were taken on components from three injection pumps. The components checked were the cam ring, the cam roller follower, and the cam roller shoe. Table 6, shows the hardness values for the pumps and components checked. All components averaged above RC 60, and appeared consistent.

Table 6. Delphi Pump Component Rockwell "C" Hardness Values

Core Pump: F1000	CAM	62.8	63.1	62.4	62.76 avg.
	ROLLER	62.6	62.4	62.7	62.56 avg.
	SHOE	61.0	60.7	62.5	61.40 avg.
SN: 09141EXG	CAM	63.2	63.5	63.6	63.43 avg.
	ROLLER	61.3	61.9	61.8	61.66 avg.
	SHOE	62.0	62.3	61.4	61.90 avg.
SN: 11589CYG	CAM	62.0	62.7	62.9	62.53 avg.
	ROLLER	61.5	61.9	61.8	61.73 avg.
	SHOE	60.8	60.9	60.9	60.86 avg.
SN: 41621FZG	CAM	62.6	62.9	63.1	62.86 avg.
	ROLLER	61.2	60.5	61.1	60.93 avg.
	SHOE	61.8	60.6	62.5	61.63 avg.

4.2.6 Test No. 6: F3000 then switched to F1000

Modifications to the test stand drive system were made to improve alignment and durability, and to determine if driveline issues may have affected the fuel injection pump durability with the low lubricity fuels. The Delphi rotary pump stand operated for 96 hours on DF-2 (F3000) without any driveline issues using a core pump built with serviceable components. At the conclusion of the 96 hours, the test stand fuel system was flushed and S-8 fuel was introduced into the stand. The test stand was operated for 79 hours on S-8 (F1000) fuel before the injected fuel quantity deteriorated. The injection quantity deteriorated by 50% when the run was terminated. Likewise there was an increase in the pump return temperature that indicates increased internal friction. Removal of the top cover revealed typical wear debris seen with low lubricity fuels in rotary fuel injection pumps. The core pump was a four-cylinder pump, the flow rate with this pump was low

compared to the other Delphi pumps evaluated due to increased internal leakage and lower cylinder count. The test stoppage due to the injection flow decrease was based on comparison to the injected flow from the pump during the initial hour of testing with the S-8 (F1000) fuel. The hours achieved on the S-8 fuel, over previous attempts to run the S-8 fuel, are in part due to the improved driveline stability and increased clearances due to the used parts. However only 79 hours durability on the S-8 (F1000) fuel would be considered poor lubricity performance.

4.2.7 Test No. 7: F3000 (DF-2)

A Delphi rotary pump completed the scheduled 500 hours of operation with the F3000 fuel. The fuel injection pump was sent to a local diesel service company for the 500 hour flow performance check and looked to meet the calibration specifications at the end of test. The injected quantity rate has slightly increased as the Delphi pump has run-in on the F3000 fuel. The governor action appears to be slightly advanced, governor starts reducing fuel at a lower speed. Inspection of pump after the top cover was removed revealed no evidence of any discoloration or wear debris.

4.2.8 Test No. 8: Fuel Blend + 22.5-ppm DCI-4A

Test stand calibration indicated the pump at 250 hours with S-8/Jet A and 22.5 ppm DCI-4A had a flow rate decrease of approximately 23 percent, and was performing similar to the pump that was evaluated for 500 hours with the neat Jet A fuel. Figure 10 shows the top of the pump with the cover removed and evidence of some wear debris. However the wear debris seen with this pump is a few larger particles, whereas the previous pumps revealed large quantities of very fine wear debris. Based on the calibration data this pump on an engine would be low on power above 2400 rpm and have compromised over-speed protection.

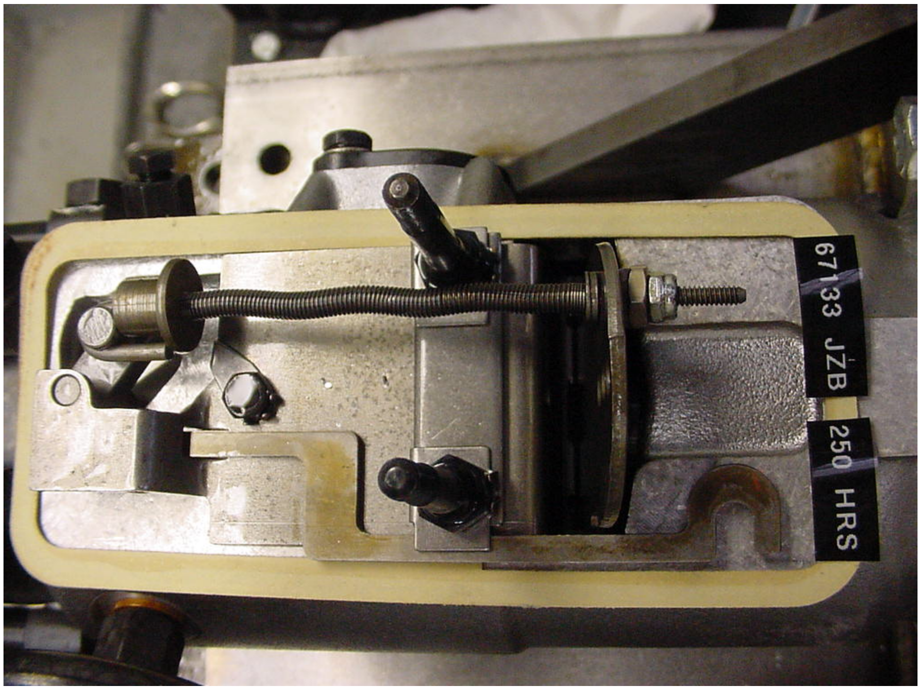

Figure 10. Pump Housing with Wear Debris for S-8/Jet A + 22.5 ppm DCI-4A Fuel Blend at 250 hours

Figure 11 is the metering valve from the test pump revealing an unusual wear pattern. The governor thrust washer from the S-8/Jet A + 22.5 ppm DCI-4A test revealed the highly unusual wear pattern shown in Figure 12. The thrust washer appeared to stop rotating and distinct wear scars formed from the action of the governor weights. Figure 13 shows a thrust washer with a more typical wear pattern. Other components of the governor linkage also revealed larger than normal wear scars.

The pumping plungers, Figure 14, from the S-8/Jet A + 22.5 ppm DCI-4A test revealed wear that caused them to cock in their bores when pressure was applied to measure the roller-to-roller dimension. The roller shoes in Figure 15 revealed substantial wear scars on the sides contacting the pumping plungers.

Another unusual result with the S-8/Jet A + 22.5 ppm DCI-4A fuel was evidence of distress on the distributor rotor discharge ports as revealed in Figure 16. The wear pattern appears to look like cavitation erosion rather than chipping. There was no evidence that the material removed from around the ports affected wear in other parts of the fuel injection pump. Chipping would

have resulted in scoring of the hydraulic head and rotor around the port area, but scoring was not evident. All parts observations are included in Table 7.

Figure 11. Delphi Rotary Fuel Injection Pump Metering Valve after 250 hours with S-8/Jet-A + 22.5-ppm DCI-4A Fuel

Figure 12. Wear Scars on Governor Thrust Washer from Governor Weights at 250 hours with S-8/Jet A + 22.5 ppm DCI-4A Fuel

Figure 13. Delphi Thrust Washer with Typical Wear Pattern after 500 hours Jet A Fuel

Figure 14. Delphi Pumping Plunger Wear Scars after Operation with S-8/Jet A + 22.5 ppm DCI-4A Fuel

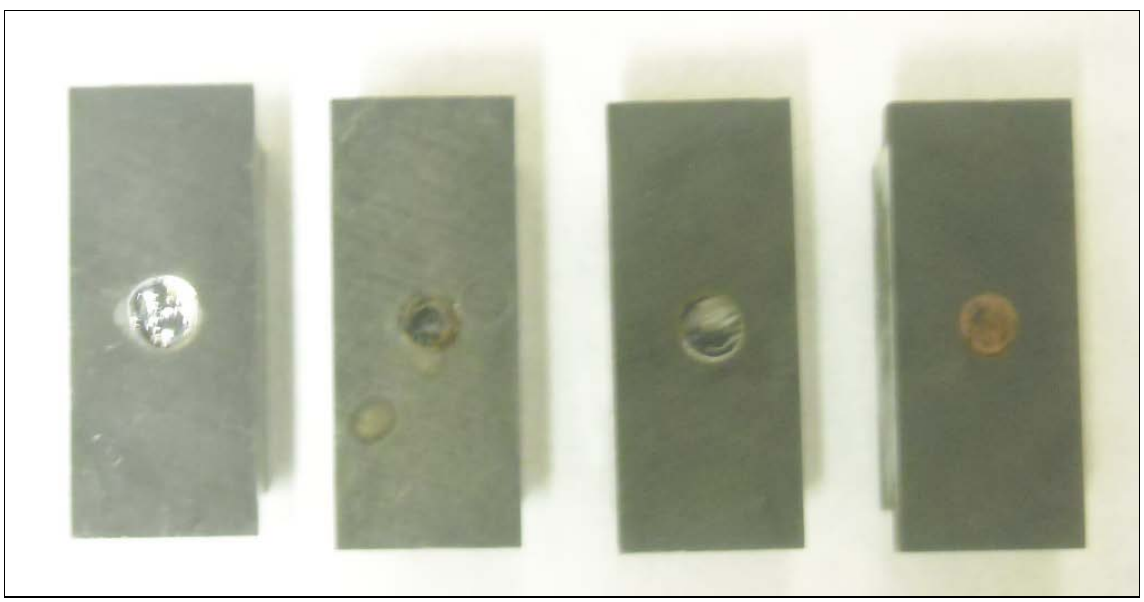

Figure 15. Roller Shoes Reveal Wear Scars at Pumping Plungers Contact Locations

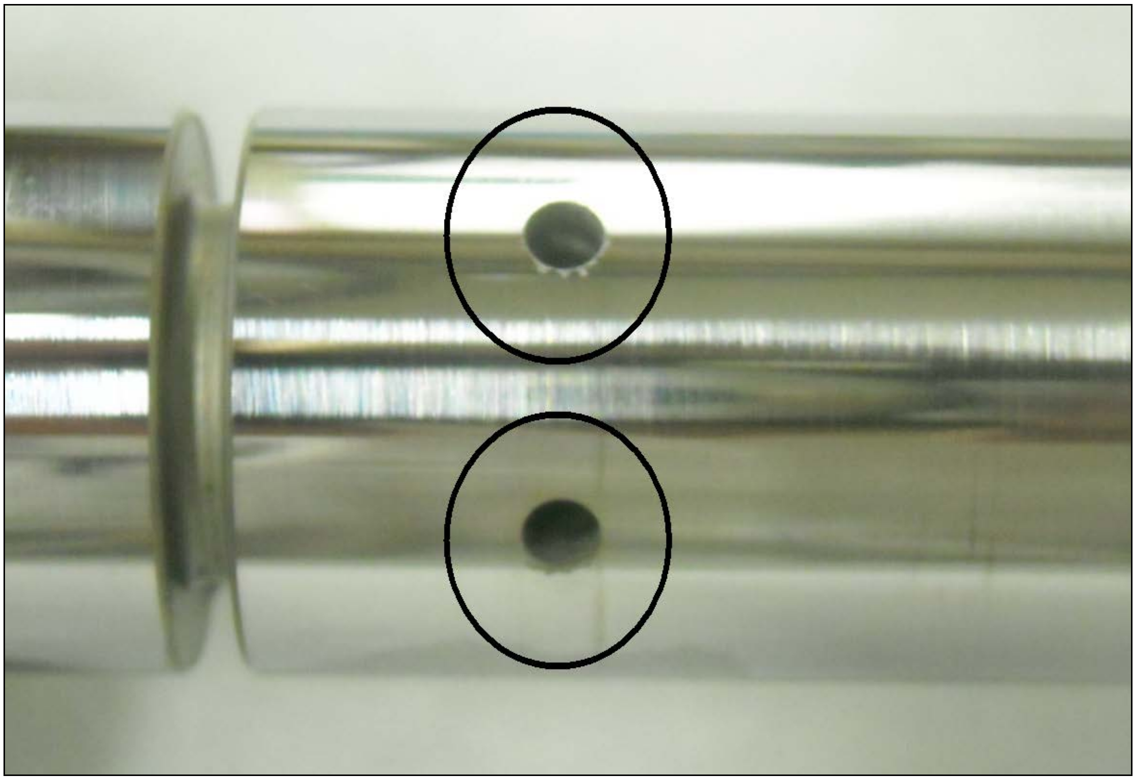

Figure 16. Delphi Rotary Fuel Injection Pump Distributor Rotor showing Evidence of Distress at Discharge Ports

Table 7. Delphi Fuel Injection Pump Parts Condition Observations

Pump Type : 3062F304	**SN: 67133JZB**	
Test condition : 250hrs 50/50 Blend S8/Jet A + 22.5ppm DCI-4A	**AL: 27550 (PUMP)**	

Part Name	Condition of part
BLADES	Replaced at Diesel Injection (Factory Warranty) - Before test. Normal light wear - Post Test.
LINER	Replaced at Diesel Injection (Factory Warranty) - Before test. Normal wear with light scratches - Post Test.
END PLATE	Very slight wear pattern.
REG. PISTON	Normal Wear.
ROTOR	Light scratches. Chipping at distributor ports.
PLUNGERS	Very worn. Moved freely in their working area but stuck when pushed through to remove.
SHOES	Replaced before test by Diesel Injection. Wear on back - plunger contact. No significant wear at adjusting plate contact. Roller contact looks normal.
ROLLERS	Replaced before test by Diesel Injection. No visible wear.
ADJUSTING PLATES	Top - Wear marks from rollers. No significant wear from shoe contact. Bottom - Wear marks from rollers. No significant wear from shoe contact.
CAM RING	Looks about the same as it did before test. Had some wear marks before test but was not replaced.
THRUST. WASH.	Unusual wear pattern from the foot of the weights. There is four weights and there was six grooves worn into the washer. Normally the wear scar is consistent around the surface of the washer.
THRUST. SLEEVE.	Worn from fingers of governor arm.
GOV. WEIGHTS	Heavy wear on foot from washer contact. Wear on heel from weight cage contact.
LINK HOOK	Groove worn into linkage long spring retainer.
M-VALVE	Unusual chatter wear marks on valve.
DR. SHAFT SPLINE	Normal Wear.
DR. SHAFT SEAL AREA	Worn from seal contact. Some wear at bearing pilot contact.
ADV. PISTON	Normal Wear. One scratch.
HOUSING	Normal Wear.
R/R DIMENSION - A/E	1.9930" Before test. As rec. from factory. Diesel Injection adjusted on the stand starting point unknown. After test - 1.9870"
R/R DIMENSION - D/H	1.9930" Before test. As rec. from factory. Diesel Injection adjusted on the stand starting point unknown. After test - 1.9864"

4.2.9 Test No. 9: Jet A (F2000) + 22.5 ppm DCI-4A

A Delphi pump completed 500 hours with the F2000+22.5 ppm DCI-4A fuel. When the pump was put on the stand after changing the head and rotor, there appeared to be a surging at the test speed. It was felt the surging would cause excessive drive loadings so the rack stop was adjusted to eliminate the surge. The change of the rack stop increased the fuel delivery, but eliminated the surge. The delivery characteristics of the pump on the stand did not change from the 122 hour point to the 500 hour point. The pump rack stop was set back to the original value and the flow evaluated on the TFLRF stand prior to sending the pump to the flow performance stand. The pump delivery flow did not change from the 122 hour pre-adjustment change. The Delphi fuel injection pump appeared to function normally after 500 hours operation with F2000+22.5 ppm DCI-4A fuel.

4.3 ULTRA LOW SULFUR DIESEL FUELS

Seven 55-gallon drums of SASOL Fischer-Tropsch process derived ULSD fuel (CAF-7199) were obtained for fuel lubricity testing. The HFRR and SLBOCLE lubricity tests were performed, and revealed that the test fuel was highly additive treated to improve fuel lubricity. The lubricity additive used was not known, nor was it known if it was on a QPL, so three drums of the fuel were clay-filtered to remove the additives. The bench test lubricity results for the fuel as received and each of the clay-filtered drums are shown in Table 8. The scuffing load result looks high for drum 2, but all the HFRR values look consistent for the clay-filtered batches. In addition a commercial ULSD (AF-7257) was obtained and clay-filtered to remove any lubricity improver additive, and a sample blend made with the SASOL fuel.

Table 8. Clay-Filter Results for SASOL Fuel CAF-7199

Fuel	ASTM D6079 WSD @ 60°C, mm	ASTM D6078 Scuffing Load, grams
CAF-7199 as received	0.332	4450
CAF-7199 Drum 1 Clay-Filtered	0.575	1800
CAF-7199 Drum 2 Clay-Filtered	0.611	2700
CAF-7199 Drum 3 Clay-Filtered	0.602	1500
AF-7257 ULSD Clay Filtered	0.602	1600
50% CAF-7199 / 50% AF-7257	0.584	1800

4.3.1 Test No. 10: Clay-Filtered SASOL Synthetic ULSD

A test with the clay-filtered SASOL test fuel in the Delphi rotary fuel injection pump was performed and terminated at 201 hours. During the first 20 hours of testing the fuel delivery was very consistent as shown in Figure 17. After 20 hours the fuel delivery started dropping off, and the pump speed was adjusted at one point to determine if the drop-off in delivery was due to governor action coming in at a lower speed. The fuel delivery was recovered at a lower speed, which suggests wear is occurring in the governor section.

The rotary fuel injection pump test was eventually terminated at 201 hours due to compromised governor action. Wear in the governor section of the fuel injection pump was causing the injection pump to severely reduce injection fuel flow at the rated speed condition. The fuel injection pump was operated on a flow performance stand with the results shown in Table 9. The shaded areas in Table 9 are operating conditions that are out of specification, marginally in specification, or conditions that could impact engine operation. It was noted some calibration parameters were off when new, but came into specification after the run-in. The pump roller-to-roller dimension controls maximum delivery, and is set prior to testing by TFLRF, and is not changed by the calibration facility per TFLRF instructions. Flow readings may be off due to the tolerance stack up of the rotor , plungers, plunger bore, roller shoes, rollers, and helical stop plate.

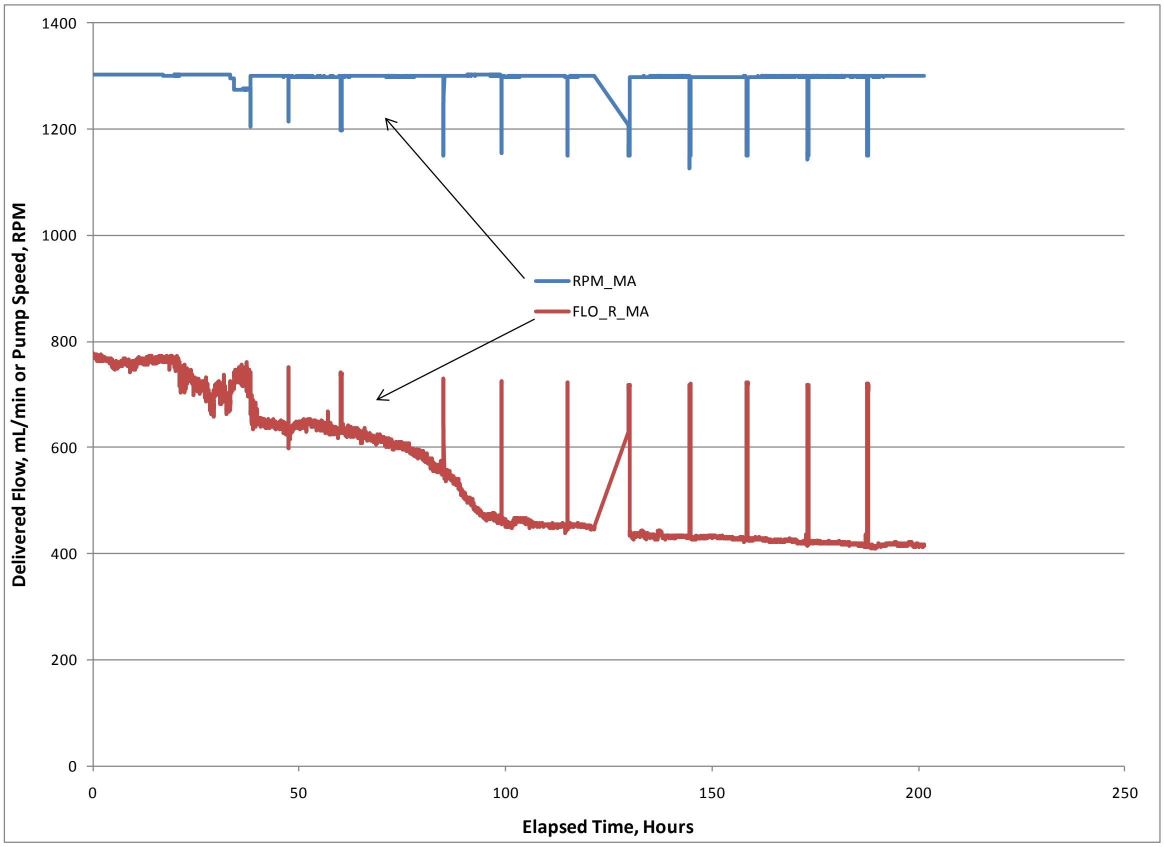

Figure 17. Fuel Delivery and Pump Speed for Delphi Pump with Clay-Filtered SASOL Fuel over Test Duration

Table 9. Delphi Flow Performance Results After Clay-Filtered Synthetic ULSD Operation

DELPHI DPA Rotary Pump					
Model Number:	3062F304	Range	Results, Flow in cc/1000 Strokes except where noted		
Test Operation	RPM	Serial Number:	01749LAB		
Date			5/21/2008	5/21/2008	5/17/2010
Comments			new	run-in	clay-filter synfuel
Hours			0	2	201
Cal. Fluid			Cal. Fluid	Cal. Fluid	Cal. Fluid
Test Fluid			-	Cal. Fluid	CAF-7199
Transfer Pressure	1200	77 to 92 psi	100	86	81
Fuel Delivery	1200	110 cc ± 1.1 Max. Spread 11.0	115	115	110
Housing Pressure	1200	No Spec.	0	0	0
Fuel Delivery (Gov.)	1430	2 cc Max.	2.5	2	3.6
Transfer Pressure	100	10 psi Min.	15	12	10
Advance	150	0.5 deg.	0.5	0.5	0.5
Advance	300	5.75 to 6.25 deg.	5.75	5.75	5.75
Cranking Fuel Delivery	100	90 cc Min.	100	100	91
Fuel Return	1200	10 to 110 cc/100 Strokes	68	69	60
Idle	300	3cc (No Spec.)	1	3	8
Complete Breakaway	1445	No Spec.	0.5	0.5	1.4
Shutoff Lever & Solenoid	200	0.8 cc max	0.5	0.5	0.5
Idle Governor	325	No Spec.	0	1	11
Record Fuel Delivery	1300	1200 RPM del. -4cc	116	116	56.0
Transfer Pressure	1300	No Spec.	100	95	95
Transfer Pressure	1430	No Spec.	120	115	103
Fuel Delivery	1430	2 cc Max.	2.5	2	2.9

4.3.2 Test No. 11: SASOL/ULSD Blend with Lubrizol 539D (65 ppm)

Table 10 shows lubricity results for the clay-filtered test fuel blend (50% CAF-7199 / 50% AF-7257) with four different levels of a U.S. Navy approved fuel lubricity additive. A sample was made at the maximum treat rate of 200 ppm and one sample at 100 ppm. The HFRR test did not appear to distinguish a significant difference between the two treated samples, as the repeatability of the method is 0.05 mm. The BOCLE wear scars were not determined for the samples, because it was felt the Scuffing Load BOCLE and HFRR were more representative tests of the wear exhibited by fuels in diesel rotary fuel injection pumps. The test fuel blend at 50 ppm additive treatment exceeded the 0.520 mm Wear Scar Diameter (WSD) specified in ASTM D 975 for ULSD fuels. An additional 15 ppm additive (65 ppm total) was added to the blend and the resulting WSD was measured at 0.470 mm with the HFRR.

Table 10. Fuel Lubricity Results for Clay-Filtered Synthetic and Certification ULSD

Sample Code	Description	Additive Treatment, ppm	ASTM D6079, mm
10-1076	50% CAF-7199 / 50% AF-7257	0	0.564
10-1077	50% CAF-7199 / 50% AF-7257 + 100 ppm Lubricity Additive	100	0.400
10-1078	50% CAF-7199 / 50% AF-7257 + 200 ppm Lubricity Additive	200	0.444
10-1352	50% CAF-7199 / 50% AF-7257 + 50 ppm Lubricity Additive	50	0.540
10-1354	50% CAF-7199 / 50% AF-7257 + 65 ppm Lubricity Additive	65	0.470

The Delphi rotary fuel injection pump successfully completed 500 hours of operation with the lubricity additive treated SASOL/ULSD blend. The side cover of the pump was removed and inspections revealed the pumps to be clean and free of any wear debris. The top cover of the pump was removed and inspections revealed the pumps to be clean and free of any wear debris.

4.4 DDC UNIT INJECTOR TESTS

In lieu of the difficulties with the RATT testing for unit injector wear, an alternate proposed approach was to modify an USN 4-71N engine to be used as an injection rig. The DD 4-71N engine was used because several unit injector rating tools were available for rating and inspecting 71 series injectors. The benefits of using the motored engine, as the injection rig is that proper injector and cam alignment and stiffness would be maintained during the course of testing. An additional benefit was that four injectors could be evaluated during one test interval, and the fuel supply to the injectors was modified so that four separate fuels could be evaluated during one test interval.

4.4.1 DDC Unit Injector Test 1

The Detroit Diesel Unit Injector rig test completed the 500 hours of operation, with differing test fuels in each of the four unit injectors, with all unit injectors functionally operational. Unit injector inspections for the various fuels and Test 1 are included as Appendix A. Overall the delivery performance of the injector did not change with any of the test fuels. All injectors exhibited some leakage around the rack and some tip wetness at 500 hours. All injectors showed

a decreased pressure drop time from 250 hours onward. The decreased pressure drop time is an indication of increased internal injector leakage between the lapped injector component surfaces. If internal leakage is substantial, the internal leakage could affect pressure development and injection timing. The wear ratings revealed that the most severe fuel was with the F2000+22.5 ppm DCI-4A blend. A surprise was the minimal wear seen with the F1000 fuel compared to both the F2000 fuels. The F3000 fuel had the least overall wear. The variation in wear is possibly due to variation in the fit of the barrel and plunger components.

The ASTM D 6079 High Frequency Reciprocating Rig wear scars were evaluated for the test fuels as blended, and after 250 hours of operation. The HFRR tests were performed at 60°C, where the repeatability of the method is 80 microns and the reproducibility of the method is 136 microns. The data in Table 11 suggest that the S-8 (F1000) fuel changed beyond the precision limits for the method, improving in lubricity value after the fuel re-circulated in the injection rig for 250 hours. The top end of the unit injector is lubricated with oil, and the migration of lubricating oil into the injector is possible. It should be noted that the fuels do appear to have discolored after operation. The low lubricity S-8 (F1000) fuel may have shown more sensitivity to contamination than the other fuels. Due to the re-circulating nature of the fuel loop in the injection rig, the accumulation of lube oil in the fuel is greater than what would be in an operating engine because there is not any consumption of fuel.

Table 11. ASTM D 6079 HFRR Wear Scar Diameters for Test Fuels

Fuel	ASTM D 6079 HFRR, WSD micron		WSD Change, micron
	0 hour	250 hour	
JET A (F2000)	724	619	105
DF-2 (F3000)	323	439	-116
S-8 (F1000)	768	408	361
JET A (F2000)+DCI4A	696	580	116

The EOT fuel samples were analyzed for lubricant additive metals from the first Detroit Diesel Unit Injector test. The results indicate that 1.5-2% dilution of lubricant in each of the test fuels, as traced by Ca, P, and Zn contents of the lube oil and fuel samples are shown in Table 12. This

level of contamination had been shown by Lacey (Ref. 1) to alter the scuffing wear results of low lubricity fuels. It is believed that this lube oil contamination is built into the design of the fuel injector, and is exacerbated by our re-circulating of fuel. This lube oil contamination could have been why there had been unusual results with the repeatability attempts with the radioactive tracer methodology; the lube oil lessens the wear rate.

Table 12. Lubricant Additive Elements in Test Fuels from Detroit Diesel Unit Injector Test

Results of the Analytical Evaluations of the Fuels and Lubricant						
	Sample Code	**CL08-00294**	**CL08-00295**	**CL08-00296**	**CL08-00297**	**AL-27619-L**
ASTM Methods	**Sample Type**	**Jet-A**	**DF-2**	**S8**	**Jet-A +DCI4A**	**Lube Oil**
D7111 Metals by ICP	Calcium	>5	>5	>5	>5	
D5185 Metal Analysis by ICP						
ppm	Aluminum	<1	<1	<1	<1	<1
ppm	Antimony	<1	<1	<1	<1	<1
ppm	Barium	<1	<1	<1	<1	<1
ppm	Boron	<1	<1	<1	<1	3
ppm	Calcium	32	41	41	31	2276
ppm	Chromium	<1	<1	<1	<1	<1
ppm	Copper	9	6	6	7	15
ppm	Iron	<1	<1	<1	<1	5
ppm	Lead	<1	<1	<1	<1	4
ppm	Magnesium	<1	<1	<1	<1	5
ppm	Manganese	<1	<1	<1	<1	<1
ppm	Molybdenum	<1	<1	<1	<1	1
ppm	Nickel	<1	<1	<1	<1	<1
ppm	Phosphorus	13	17	16	12	876
ppm	Silicon	10	7	13	9	45
ppm	Silver	<1	<1	<1	<1	<1
ppm	Sodium	<5	<5	<5	<5	12
ppm	Tin	<1	<1	<1	<1	<1
ppm	Zinc	13	19	17	13	991
ppm	Potassium	<5	<5	<5	<5	<5
ppm	Strontium	<1	<1	<1	<1	<1
ppm	Vanadium	<1	<1	<1	<1	<1
ppm	Titanium	<1	<1	<1	<1	<1
ppm	Cadmium	<1	<1	<1	<1	6

It was determined that the addition of the 0.5% engine lubricating oil to a 50%/50%-S-8/Jet-A fuel blend did change both the HFRR wear scar and SLBOCLE scuffing load values. Prior work at TFLRF had suggested 0.5% lubrication oil would have a minor effect. The response of the S-8/Jet-A blend to the lubricating oil addition (Table 13) suggest that low lubricity fuels show a positive response to lubricating oil contamination.

Table 13. Lubricity Bench Test Results with Low Lubricity Fuels and Lubricating Oil Addition

Test Method	Description / Property	Test Units	S-8/Jet A blend at 50%/50%	S-8/Jet A blend at 50%/50% with the addition of 0.5% lube oil
ASTM D6079	Lubricity by HFRR	mm	0.650	0.565
ASTM D6078	Lubricity by SLBOCLE Scuffing Load	grams	1500	2000

4.3.2 DDC Unit Injector Test 2

The DDC unit injector test rig was used to evaluate the following four test fuels; SASOL, SASOL/ULSD + additive blend, F1000, and F1000/F2000 blend. Twenty gallons of fuel for each injector were changed every 125 hours of operation, for 500 hours total. One-hundred gallons of each test fuel or test fuel blend were blended for each unit injector.

The Detroit Diesel Unit Injector rig test completed the 500 hours of operation with all unit injectors functionally operational. Unit injector inspections for the various fuels and Test 2 are included as Appendix A. Overall the delivery performance of the injector did not change with any of the test fuels. All injectors did not exhibit leakage around the rack nor any tip wetness at 500 hours. All injectors showed an increased pressure drop time. The increased pressure drop time suggests the leakage from the internal sealing surfaces was reduced, possibly leading to more consistent injection events. The wear ratings revealed that the most severe fuel was with the SASOL clay-filtered fuel. A surprise was the minimal wear seen with the F1000 fuel than compared to wear seen with the SASOL/ULSD + additive blend. The F1000/F2000 fuel blend had slightly more overall wear than the F1000 fuel. Wear was determined by visual inspection of five different areas on the unit injector plungers, and comparing the level of wear in those locations between test fuels. The variation in wear is possibly due to variation in the fit of the barrel and plunger components.

5.0 CONCLUSIONS

5.1 S-8 (F1000) ROTARY FUEL INJECTION PUMP WEAR TEST SUMMARY

All instances of rotary fuel injection pump operation with S-8, whether blended, or with additives, have resulted in excessive or premature wear of the rotary fuel injection systems. That fact suggests neither the lubricity nor the viscosity of the S-8 or S-8 blends are adequate for the rotary injection pump use, with the current additives, because there does not appear to be any margin of protection with the fuel in the Delphi fuel lubricated rotary fuel injection equipment as currently configured. The Delphi fuel lubricated rotary fuel injection pump does not have pump component modifications available for low viscosity, low lubricity fuels. Another military rotary fuel injection equipment supplier offers modified, hardened parts for use with low lubricity fuels.

5.2 JET A (F2000) ROTARY FUEL INJECTION PUMP WEAR TEST SUMMARY

Each instance of rotary fuel injection pump operation with Jet A, neat, or with additives, resulted in performance degradation of the rotary fuel injection system, but not excessive premature wear. This suggests the natural lubricity from the aromatic compounds, and additive effectiveness, does offer some protection in the Delphi fuel lubricated rotary fuel injection equipment as currently configured. However, similar fuel injection equipment in U.S. Army boats suffer chronic problems with JP-8 fuel.

5.3 F-76 (F3000) ROTARY FUEL INJECTION PUMP WEAR TEST SUMMARY

As anticipated the rotary fuel injection pump operation with F3000 fuel operated normally without any performance degradation or premature wear. The natural lubricity from the aromatic compounds, and increased viscosity, provides protection in the Delphi fuel lubricated rotary fuel injection equipment as currently configured, and would be the fuel of choice.

5.4 ULSD ROTARY FUEL INJECTION PUMP WEAR TEST SUMMARY

Two types of ULSD fuels were examined, a synthetic Fischer-Tropsch fuel with extremely low sulfur and aromatics, and a U.S. EPA 15 ppm ULSD reference fuel. Both fuels were clay-filtered to remove any lubricity additives added during refining. The rotary fuel injection pump operation with the synthetic diesel fuel revealed performance degradation and increased wear. A synthetic ULSD/petroleum ULSD blend with a QPL lubricity additive suggests the natural lubricity from the aromatic compounds, and the additive effectiveness both offer adequate protection in the Delphi fuel lubricated rotary fuel injection equipment.

5.5 UNIT INJECTOR WEAR TEST SUMMARY

The unit injectors are less prone to wear with any of the lubricity and viscosity levels of the fuels evaluated. However, the results may have been skewed by lubricant contamination of the test fuels due to the re-circulating fuel system. Migration of lubricant from the top of the injector appears to offer additional protection with low lubricity fuels.

6.0 RECOMMENDATIONS

Based on the evaluations the following recommendations are suggested:

- The F1000 fuel, synthetic kerosene, even when blended with petroleum kerosene and treated with CI/LI, does not provide adequate protection for the Delphi fuel-lubricated rotary fuel injection pump. It is recommended that the F1000 fuel or F1000 fuel blends not be used in any mission critical engine that uses the Delphi fuel lubricated rotary fuel injection equipment.
- The F2000 fuel, petroleum kerosene, can provide adequate protection from excessive wear when treated with CI/LI, but will exhibit some engine performance degradation. Long term use is not recommended for the Delphi fuel-lubricated rotary fuel injection pump.
- A synthetic ULSD / petroleum ULSD blend treated with a QPL lubricity additive is equivalent to F-76 in the Delphi fuel-lubricated rotary fuel injection pump. Its' use would be recommended.

7.0 REFERENCES

(1) P.I. Lacey, *"Evaluation of Thermally Induced Injection Pump seizures and the Effects of Lubricating Oil Addition on Aviation Turbine Fuel Lubricity,"* Letter Report No. BFLRF- 91-007, Belvoir Fuels and Lubricants Research Facility, Southwest Research Institute, San Antonio, TX, December 1991.

(2) Douglas M. Yost, *"Bridge Erection Boat (BEB) Fuel Injection Pump Evaluation,"* Interim Report TFLRF No. 396, TARDEC Fuels and Lubricants Research Facility, Southwest Research Institute, San Antonio, TX, June 2011.

APPENDIX A

Unit Injector Plunger Inspections

Lubricity

Oil Code:	F2000	Test No.:	DDUI01.P1

Plunger 1

View 1,2,3,4

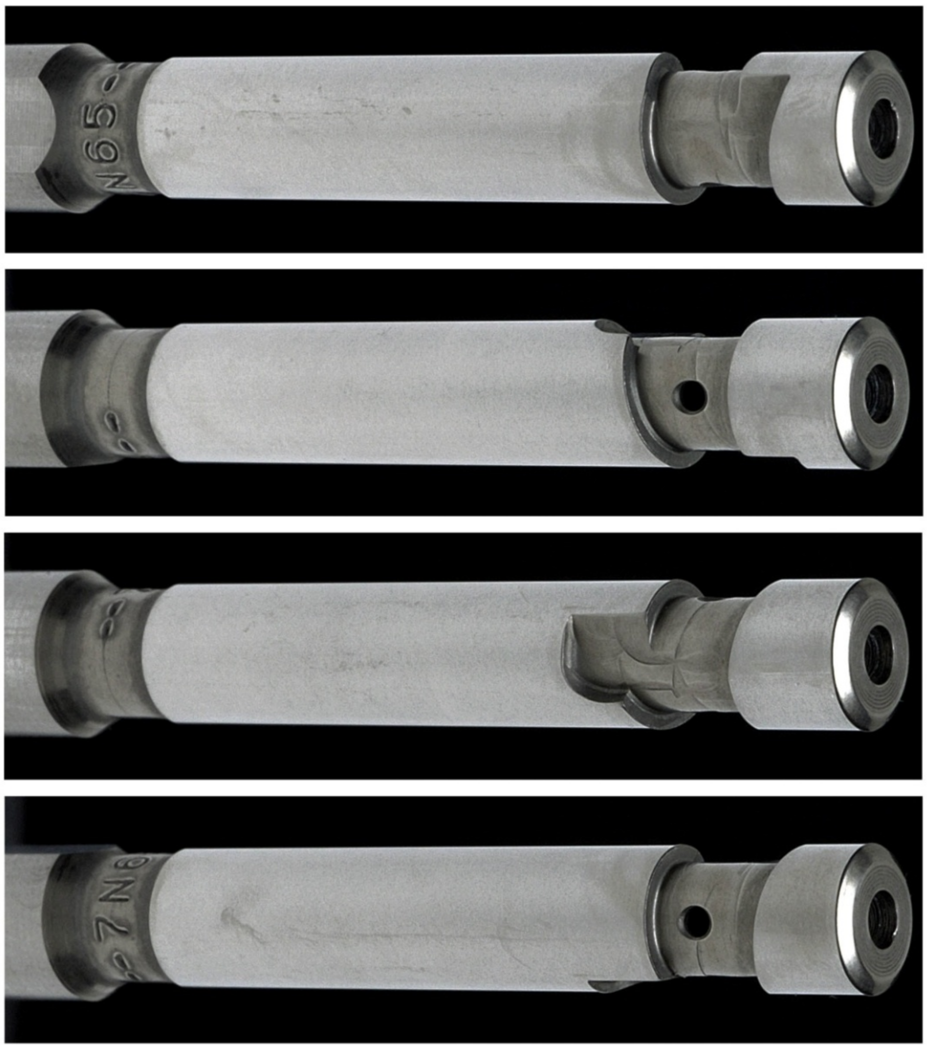

Figure A1. Plunger for Test No. 1 from Cylinder 1, F2000 Fuel at 0 Hours

Lubricity

Oil Code:	F3000	Test No.:	DDUI01.P2

Plunger 2

View 1,2,3,4

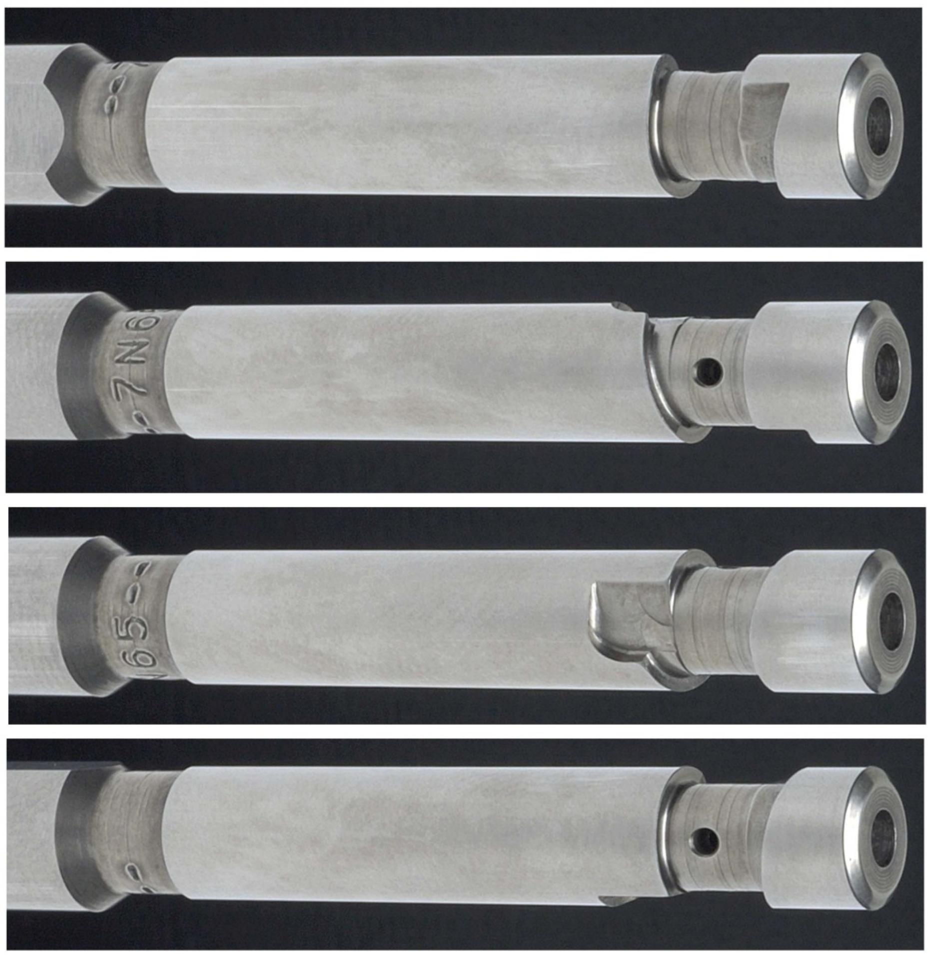

Figure A2. Plunger for Test No. 1 from Cylinder 2, F3000 Fuel at 0 Hours

Lubricity

Oil Code:	F1000	Test No.:	DDUI01.P3

Plunger 3

View 1,2,3,4

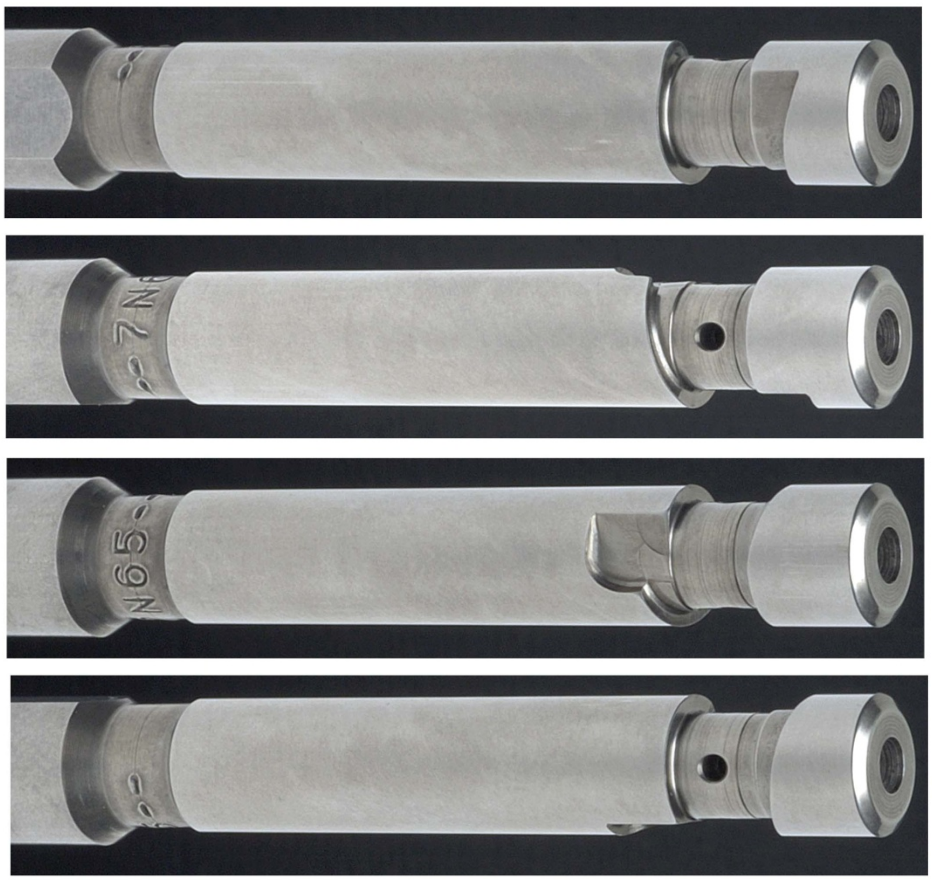

Figure A3. Plunger for Test No. 1 from Cylinder 3, F1000 Fuel at 0 Hours

Lubricity

Oil Code:	F2000+9DC14A	Test No.:	DDUI01.P4

Plunger 4

View 1,2,3,4

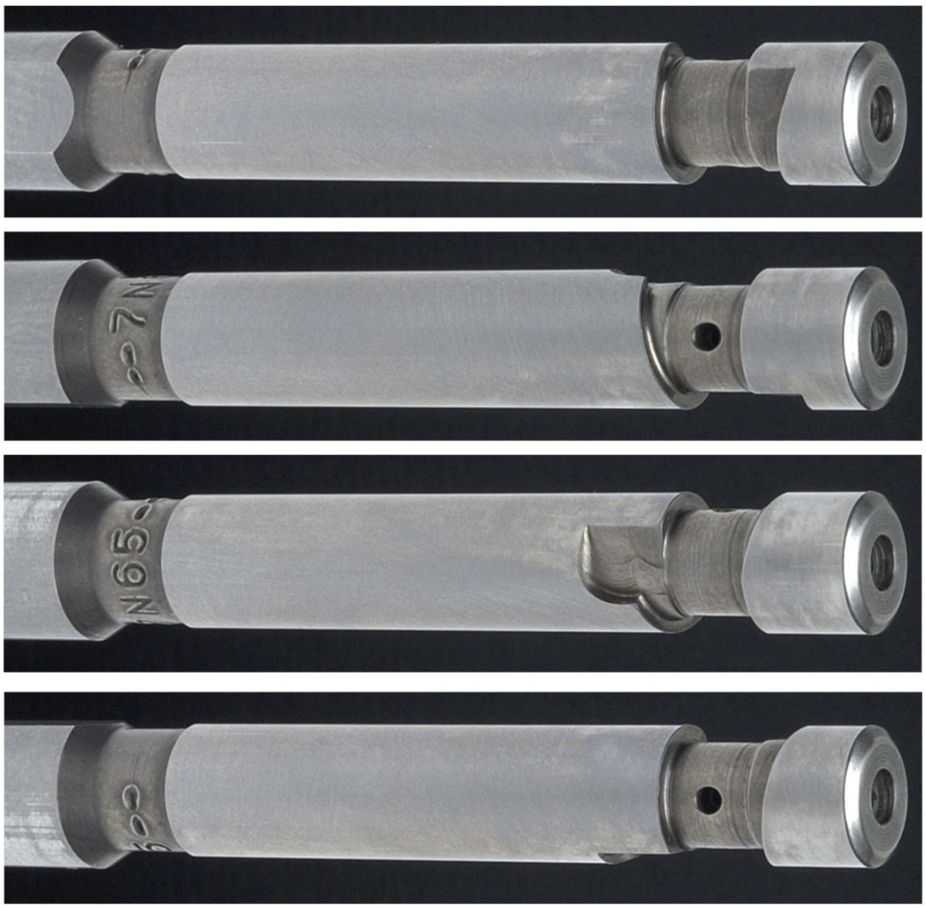

Figure A4. Plunger for Test No. 1 from Cylinder 4, F2000 + 9-ppm DCI-4A at 0 Hours

Table A1. Fuel F2000 Unit Injector Inspections

Detroit Diesel Fuel Injector Test Results

Injector Model 7N65 Injector Location DDUI01.P1
Technician REG Test Fuel No. F2000, AL-27069

Test	Units	Initial Check	Reassembly/Test Hours		Test Hours	Test Hours	
Injector Valve Opening and Spray Pattern		0	0		250	500	
Pressure Reference No.		143	143		142	140	
Spray Pattern		good	good		good	good	
Unit Hold Time							
Pressure Drop Time	sec.	54	60		36.97	20.68	
Spray Tip							
Pressure	psig	2000	2000		2000	2000	
Tip Dryness		dry	dry		dry	leak/rack	
Needle Travel							
Needle Valve Lift	in.	0.0005				0.001	
Calibration	ml/1000 strokes	34	34		34	33	
Wear	1=light 6=severe	Rating (1-6)	Weight	WTD	Rating (1-6)	Weight	WTD
Side 1	(1-6)	1	0.286	0.286	3	0.286	0.858
Side 2	(1-6)	1	0.071	0.071	2	0.071	0.142
Side 3	(1-6)	1	0.214	0.214	1	0.214	0.214
Side 3 Helix	(1-6)	2	0.286	0.572	3	0.286	0.858
Side 4	(1-6)	1	0.143	0.143	1	0.143	0.143
Total	(1-6)			1.286			2.215

Lubricity

Oil Code:	F2000	Test No.:	DDUI01.P1

Plunger 1

View 1,2,3,4

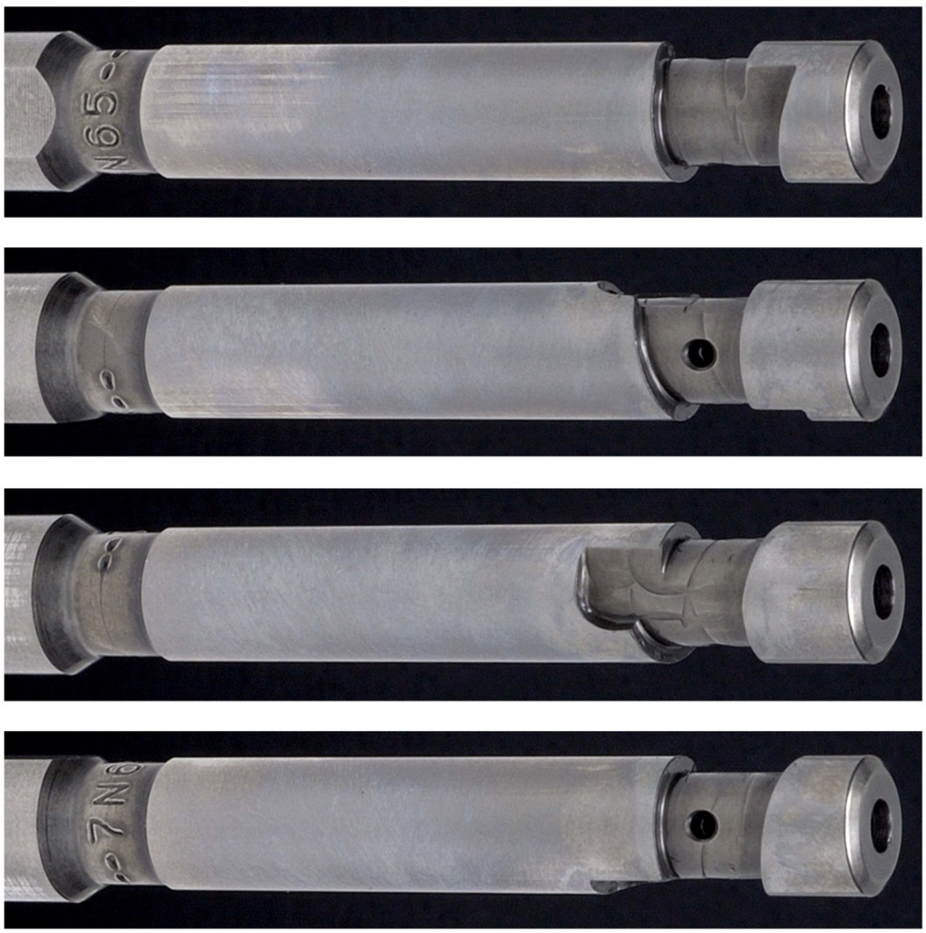

Figure A5. Plunger Conditions for Test No. 1 from Cylinder 1 for Fuel F2000 at 500 Hours

Table A2. Fuel F3000 Unit Injector Inspections

Detroit Diesel Fuel Injector Test Results

Injector Model 7N65 — Injector Location DDUI01.P2
Technician REG — Test Fuel No. F3000, AL-27169

Test	Units	Initial Check	Reassembly/Test Hours		Test Hours	Test Hours	
Injector Valve Opening and Spray Pattern		0	0		250	500	
Pressure Reference No.		142	142		141	141	
Spray Pattern		good	good		good	good	
Unit Hold Time							
Pressure Drop Time	sec.	46.43	70		32.78	30.3	
Spray Tip							
Pressure	psig	2000	2000		2000	2000	
Tip Dryness		dry	dry		dry	leak/rack	
Needle Travel							
Needle Valve Lift	in.	0.01				0.007	
Calibration	ml/1000 strokes	35	35		35	35	
Wear	1=light 6=severe	Rating (1-6)	Weight	WTD	Rating (1-6)	Weight	WTD
Side 1	(1-6)	2	0.286	0.572	2	0.286	0.572
Side 2	(1-6)	1	0.071	0.071	1	0.071	0.071
Side 3	(1-6)	1	0.214	0.214	1	0.214	0.214
Side 3 Helix	(1-6)	2	0.286	0.572	3	0.286	0.858
Side 4	(1-6)	1	0.143	0.143	1	0.143	0.143
Total	(1-6)			1.572			1.858

Lubricity

Oil Code:	F3000	Test No.:	DDUI01.P2

Plunger 2

View 1,2,3,4

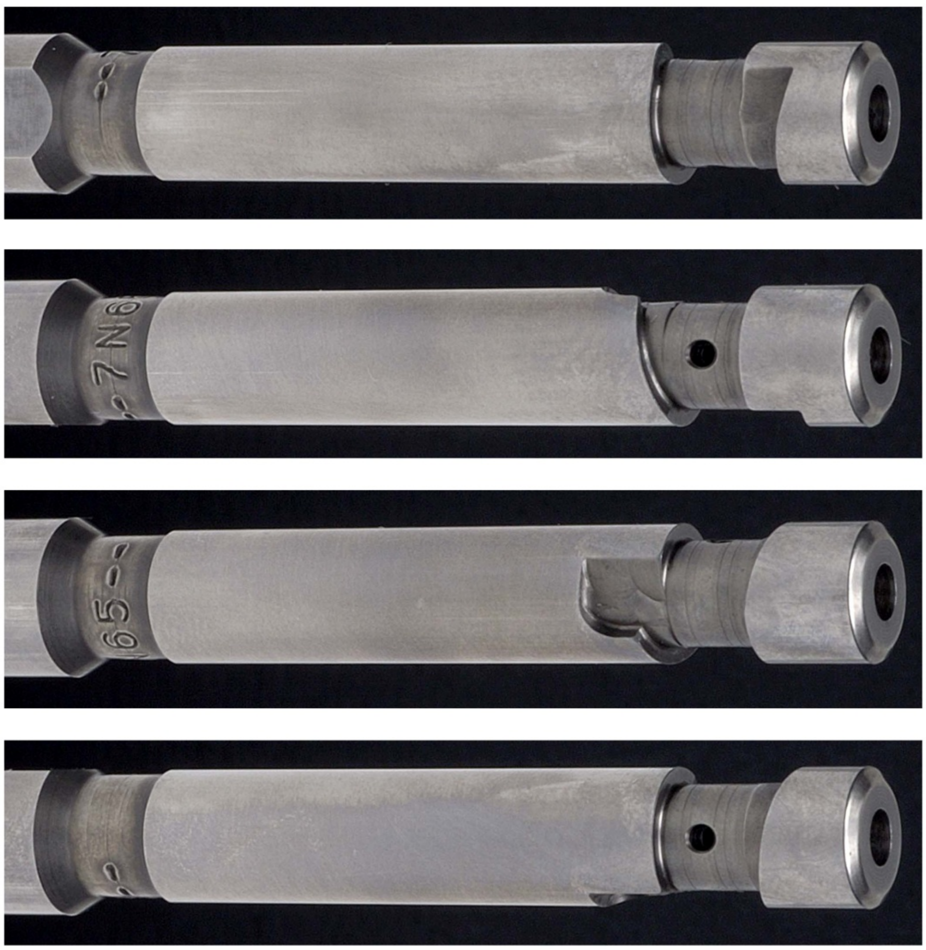

Figure A6. Plunger Conditions for Test No. 1 from Cylinder 2 for Fuel F3000 at 500 Hours

Table A3. Fuel F1000 Unit Injector Inspections

Detroit Diesel Fuel Injector Test Results

Injector Model 7N65 Injector Location DDUI01.P3
Technician REG Test Fuel No. F1000, AL-27074

Test	Units	Initial Check	Reassembly/Test Hours		Test Hours	Test Hours	
Injector Valve Opening and Spray Pattern		0	0		250	500	
Pressure Reference No.		140	140		140	138	
Spray Pattern		good	good		good	good	
Unit Hold Time							
Pressure Drop Time	sec.	75	69		37.26	34.9	
Spray Tip							
Pressure	psig	2000	2000		2000	2000	
Tip Dryness		dry	dry		dry	leak/rack	
Needle Travel							
Needle Valve Lift	in.	0.009				0.002	
Calibration	ml/1000 strokes	35	36		35	35	
Wear	1=light 6=severe	Rating (1-6)	Weight	WTD	Rating (1-6)	Weight	WTD
Side 1	(1-6)	1	0.286	0.286	2	0.286	0.572
Side 2	(1-6)	1	0.071	0.071	1	0.071	0.071
Side 3	(1-6)	1	0.214	0.214	1	0.214	0.214
Side 3 Helix	(1-6)	1	0.286	0.286	2	0.286	0.572
Side 4	(1-6)	1	0.143	0.143	1	0.143	0.143
Total	(1-6)			1.000			1.572

Lubricity

Oil Code:	F1000	Test No.:	DDUI01.P3

Plunger 3

View 1,2,3,4

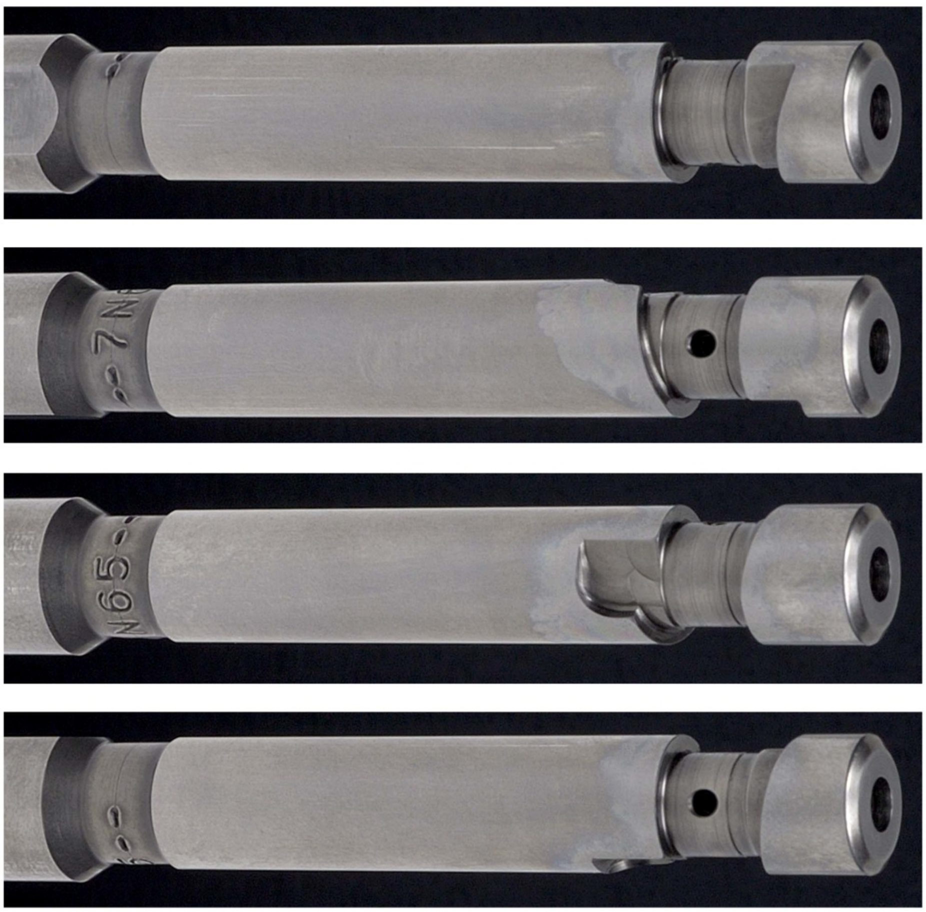

Figure A7. Plunger Conditions for Test No. 1 from Cylinder 3 for Fuel F1000 at 500 Hours

Table A4. Fuel F2000 + 22.5 ppm DCI-4A Unit Injector Inspections

Detroit Diesel Fuel Injector Test Results

Injector Model 7N65 Injector Location DDUI01.P4
Technician REG Test Fuel No. F2000+22.5-ppmDCI-4A, AL-28182

Test	Units	Initial Check	Reassembly/Test Hours		Test Hours	Test Hours	
Injector Valve Opening and Spray Pattern		0	0		250	500	
Pressure Reference No.		144	147		141	143	
Spray Pattern		good	good		good	good	
Unit Hold Time							
Pressure Drop Time	sec.	123	120		73	69	
Spray Tip							
Pressure	psig	2000	2000		2000	2000	
Tip Dryness		dry	dry		dry	leak/rack	
Needle Travel							
Needle Valve Lift	in.	0.009				0.003	
Calibration	ml/1000 strokes	34	34		34	34	
Wear	1=light 6=severe	Rating (1-6)	Weight	WTD	Rating (1-6)	Weight	WTD
Side 1	(1-6)	1	0.286	0.286	3	0.286	0.858
Side 2	(1-6)	1	0.071	0.071	3	0.071	0.213
Side 3	(1-6)	1	0.214	0.214	3	0.214	0.642
Side 3 Helix	(1-6)	2	0.286	0.572	5	0.286	1.43
Side 4	(1-6)	1	0.143	0.143	3	0.143	0.429
Total	(1-6)			1.286			3.572

Lubricity

Oil Code:	F2000+22.5DCI4A	Test No.:	DDUI01.P4

Plunger 4

View 1,2,3,4

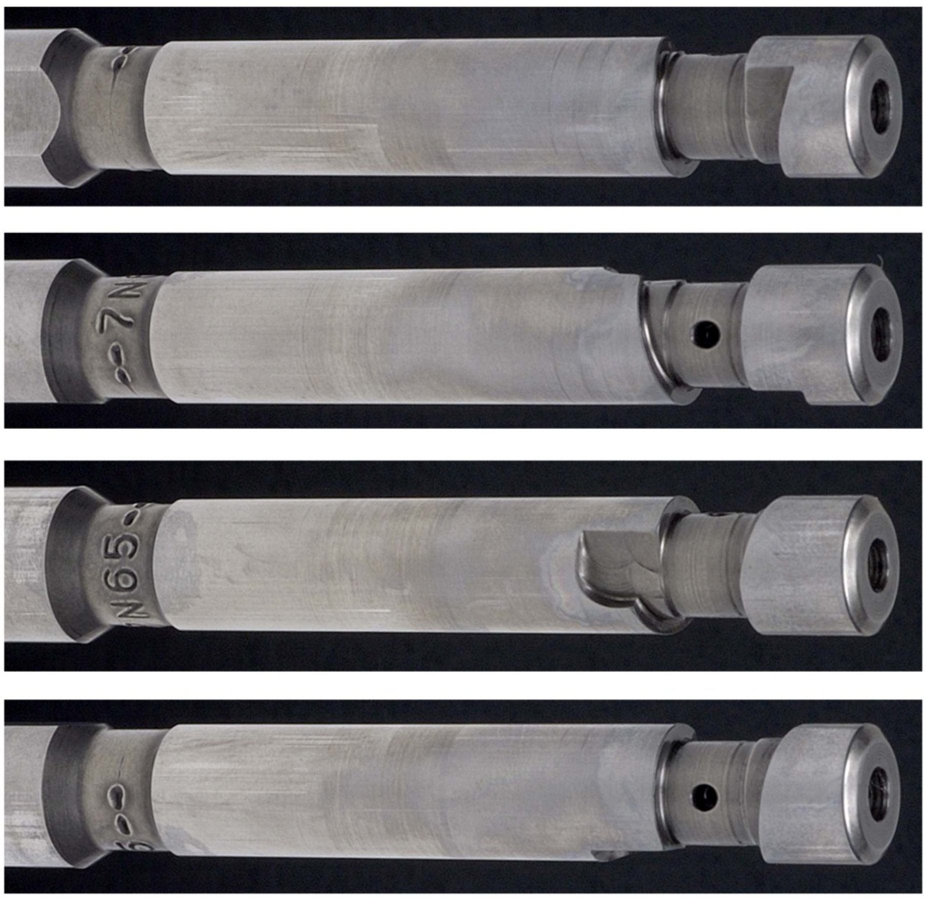

Figure A8. Plunger Conditions for Test No. 1 from Cylinder 4 for Fuel F2000+22.5 ppm DCI4A at 500 Hours

Lubricity

Oil Code:	F3000	Test No.:	DDUI02.P1	Test Hours:	0

Plunger 1

View 1,2,3,4

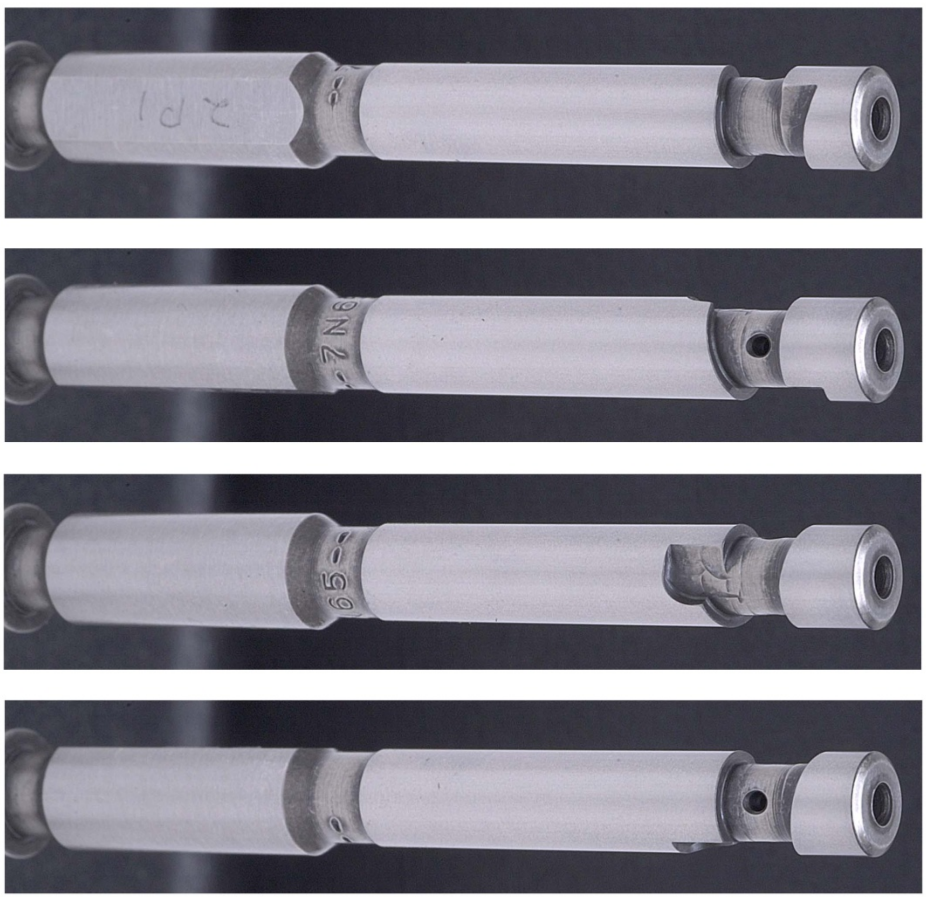

Figure A9. Plunger Condition for Test No. 2 Cylinder 1, SASOL Clay-filtered Fuel at 0 Hours

Lubricity

Oil Code:	F2000	**Test No.:**	DDUI02.P2	**Test Hours:**	0

Plunger 2

View 1,2,3,4

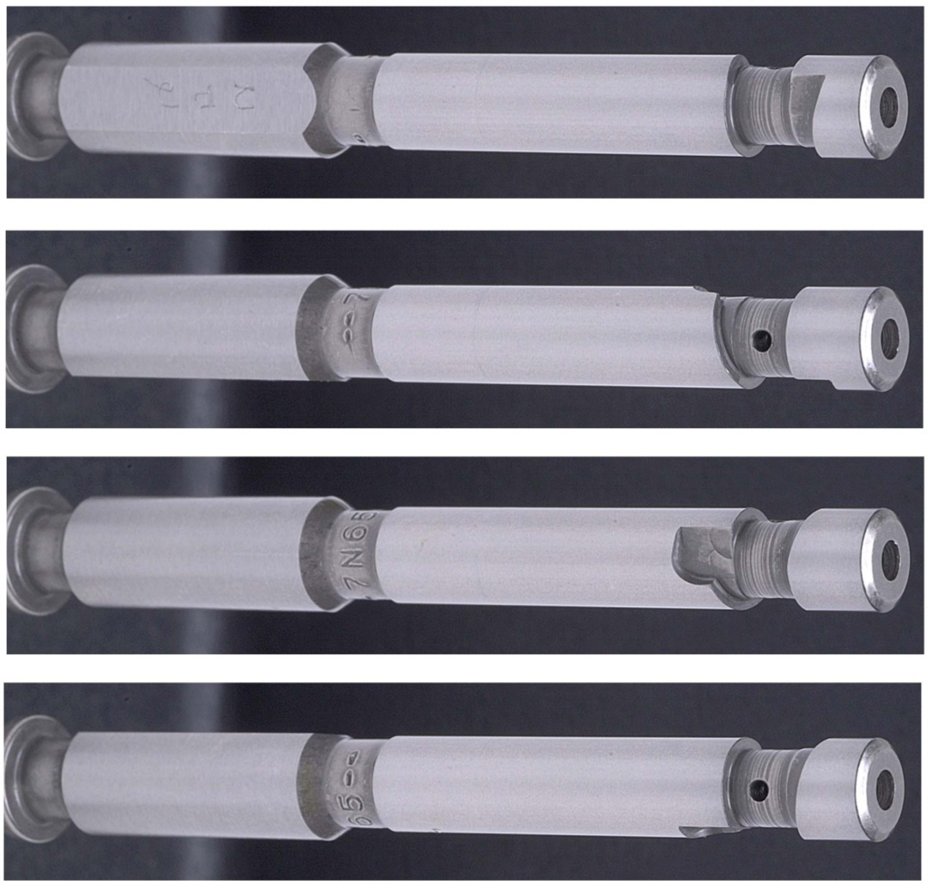

Figure A10. Plunger Condition for Test No. 2 Cylinder 2, SASOL/ULSD Clay-filtered +Lubrizol 539D Fuel at 0 Hours

Lubricity

Oil Code:	F2000+9DCI4A	**Test No.:**	DDUI02.P3	**Test Hours:**	0

Plunger 3

View 1,2,3,4

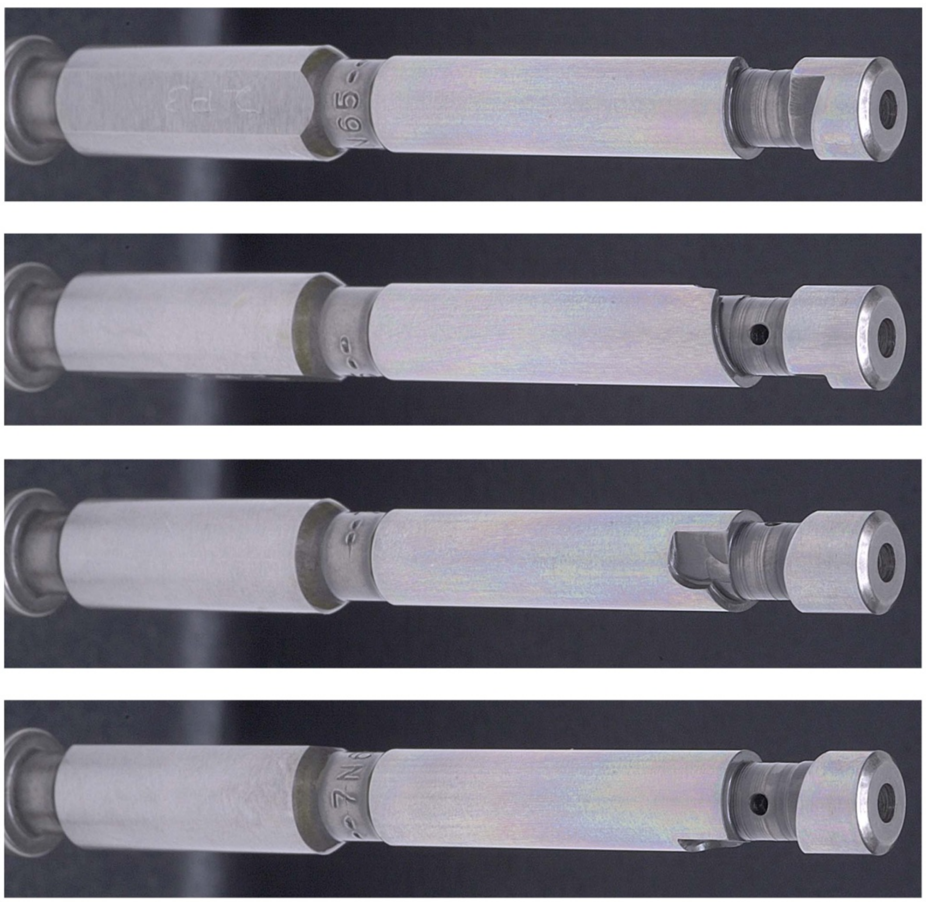

Figure A11. Plunger Condition for Test No. 2 Cylinder 3, F1000/F2000 Fuel at 0 Hours

Lubricity

Oil Code: F1000	Test No.: DDUI02.P4	Test Hours: 0

Plunger 4

View 1,2,3,4

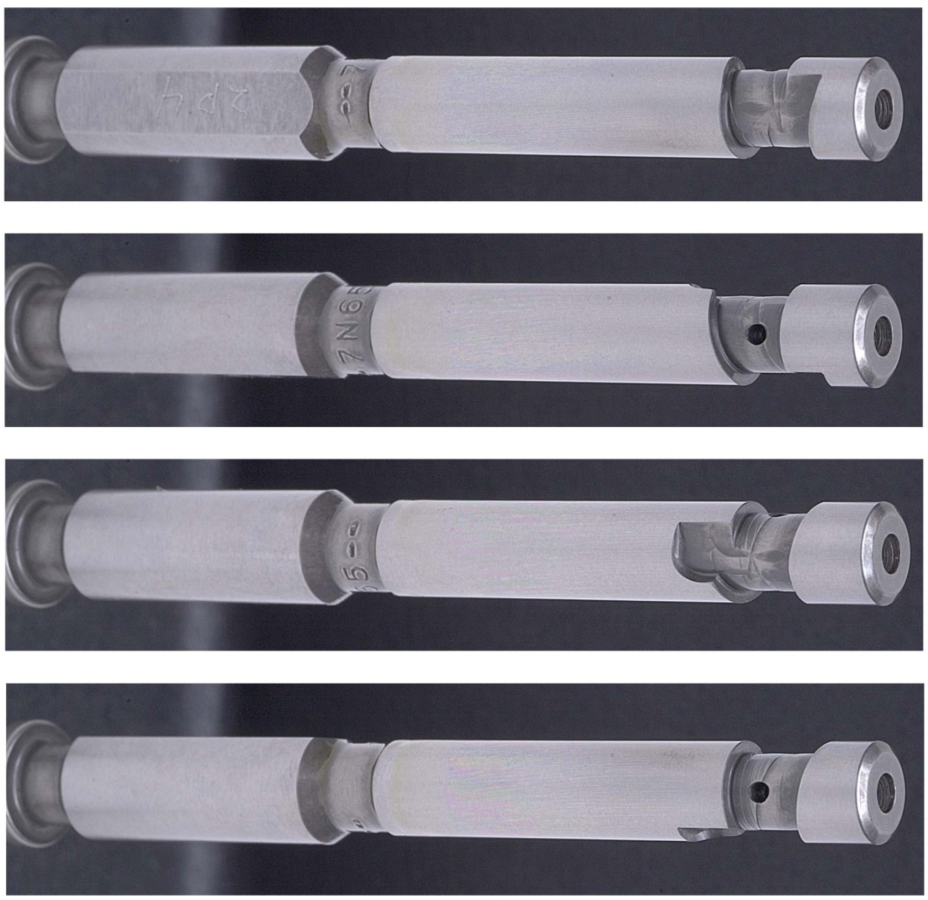

Figure A12. Plunger Condition for Test No. 2 Cylinder 4, F1000 Fuel at 0 Hours

TableA5. Clay-Filtered Synthetic Diesel Fuel Unit Injector Inspections

Detroit Diesel Fuel Injector Test Results

Injector Model: 7N65
Technician: REG
Injector Location: DDUI02.P1
Test Fuel No.: SASOL (CAF-7199 clay-filtered)

Test	Units	Initial Check	Reassembly Test Hours			Test Hours	Test Hours		
Test Hours			0				500		
Injector Valve Opening and Spray Pattern									
Pressure Reference No.			147				140		
Spray Pattern			Good				Good		
Unit Hold Time									
Pressure Drop Time	sec.		397				420		
Spray Tip									
Pressure	psig		2000				2000		
Tip Dryness			Dry				Dry		
Needle Travel									
Needle Valve Lift	in.		0.0095						
Calibration	ml/1000 strokes		32				34		
Wear	1=light 6=severe		(1-6)	Weight	Wtd		(1-6)	Weight	Wtd
Side 1	(1-6)		1	0.286	0.286		2	0.286	0.572
Side 2	(1-6)		1	0.071	0.071		1	0.071	0.071
Side 3	(1-6)		1	0.214	0.214		1	0.214	0.214
Side 3 Helix	(1-6)		1	0.286	0.286		3	0.286	0.858
Side 4	(1-6)		1	0.143	0.143		1	0.143	0.143
Total	(1-6)				1				1.858

Lubricity

Oil Code:	SASOL (clay filtered)	**Test No.:**	DDUI02.P1	**Test Hours:**	500

Plunger 1

View 1,2,3,4

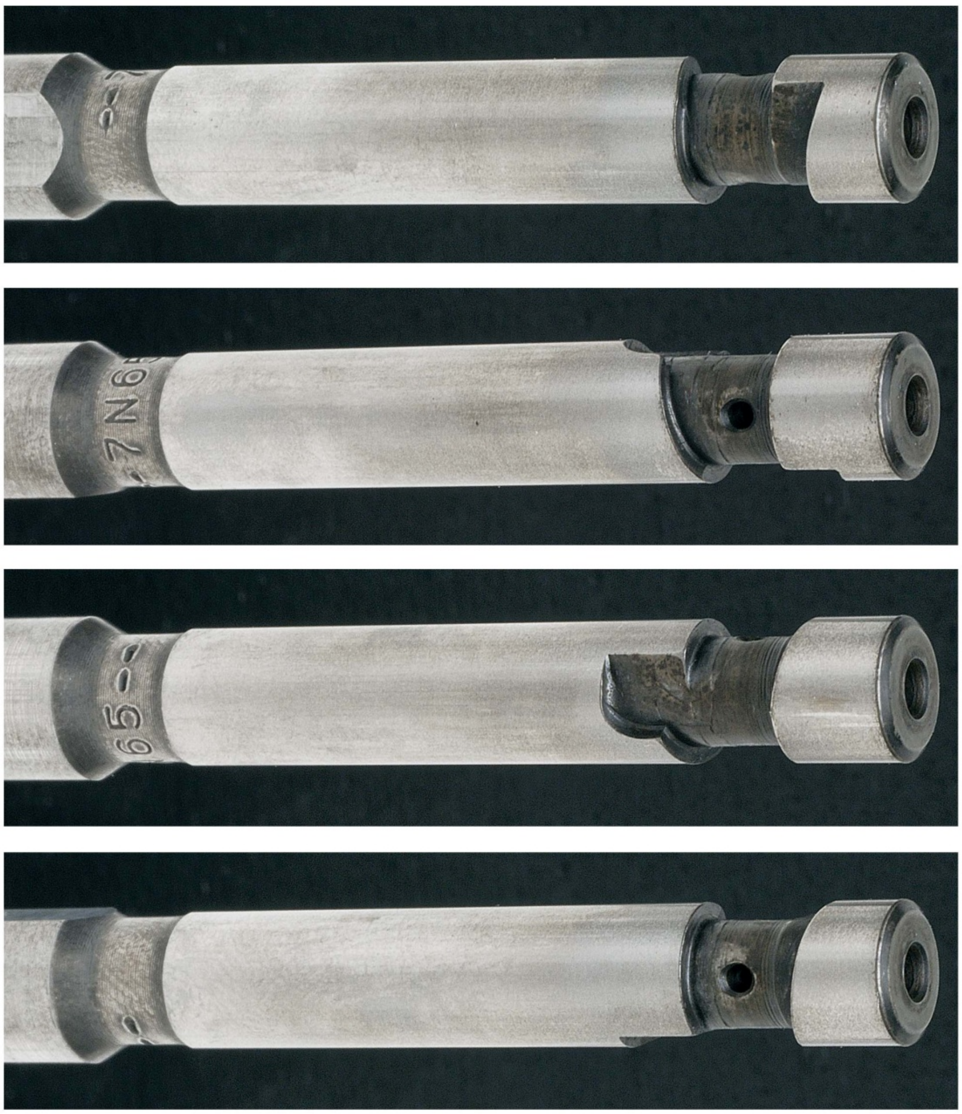

Figure A13. Plunger Condition for Test No. 2 Cylinder 1, SASOL Clay-filtered Fuel at 500 Hours

Table A6. Clay-Filtered Synthetic Diesel/ULSD + Lubrizol 539D Fuel Unit Injector Inspections

Detroit Diesel Fuel Injector Test Results

Injector Model 7N65 | Injector Location DDUI02.P2

Technician REG | Test Fuel No. SASOL/ULSD (clay filtered) + Lubrizol 539D(65-ppm)

Test	Units	Initial Check	Reassembly Test Hours			Test Hours	Test Hours		
Test Hours			0				500		
Injector Valve Opening and Spray Pattern									
Pressure Reference No.			150				140		
Spray Pattern			Good				Good		
Unit Hold Time									
Pressure Drop Time	sec.		429				540		
Spray Tip									
Pressure	psig		2000				2000		
Tip Dryness			Dry				Dry		
Needle Travel									
Needle Valve Lift	in.		0.01						
Calibration	ml/1000 strokes		34				34		
Wear	1=light 6=severe		(1-6)	Weight	Wtd		(1-6)	Weight	Wtd
Side 1	(1-6)		1	0.286	0.286		1	0.286	0.286
Side 2	(1-6)		1	0.071	0.071		1	0.071	0.071
Side 3	(1-6)		1	0.214	0.214		1	0.214	0.214
Side 3 Helix	(1-6)		1	0.286	0.286		2	0.286	0.572
Side 4	(1-6)		1	0.143	0.143		1	0.143	0.143
Total	(1-6)				1				1.286

Lubricity

Oil Code:	SASOL/ULSD + L539D	**Test No.:**	DDUI02.P2	**Test Hours:**	500

Plunger 2

View 1,2,3,4

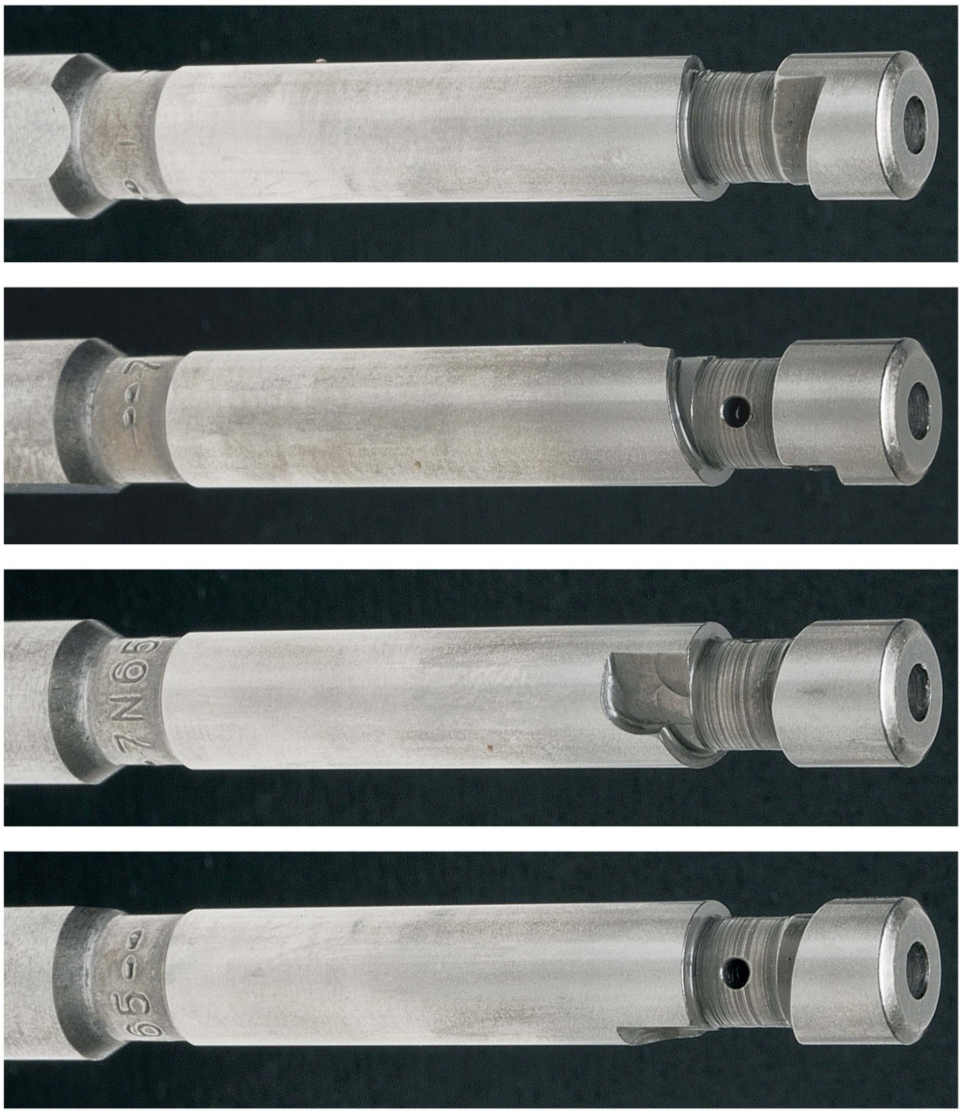

Figure A14. Plunger Condition for Test No. 2 Cylinder 2, SASOL/ULSD Clay-filtered +Lubrizol 539D Fuel at 500 Hours

Table A7. F1000/F2000 Fuel Unit Injector Inspections

Detroit Diesel Fuel Injector Test Results

Injector Model: 7N65
Technician: REG
Injector Location: DDUI02.P3
Test Fuel No.: F1000/F2000

Test	Units	Initial Check	Reassembly Test Hours			Test Hours	Test Hours		
Test Hours			0				500		
Injector Valve Opening and Spray Pattern									
Pressure Reference No.			148				136		
Spray Pattern			Good				Good		
Unit Hold Time									
Pressure Drop Time	sec.		422.6				480		
Spray Tip									
Pressure	psig		2000				2000		
Tip Dryness			Dry				Dry		
Needle Travel									
Needle Valve Lift	in.		0.009						
Calibration	ml/1000 strokes		34				34		
Wear	1=light 6=severe		(1-6)	Weight	Wtd		(1-6)	Weight	Wtd
Side 1	(1-6)		1	0.286	0.286		3	0.286	0.858
Side 2	(1-6)		1	0.071	0.071		1	0.071	0.071
Side 3	(1-6)		1	0.214	0.214		1	0.214	0.214
Side 3 Helix	(1-6)		1	0.286	0.286		1	0.286	0.286
Side 4	(1-6)		1	0.143	0.143		1	0.143	0.143
Total	(1-6)				1				1.572

Lubricity

Oil Code:	F1000/F2000	**Test No.:**	DDUI02.P3	**Test Hours:**	500

Plunger 3

View 1,2,3,4

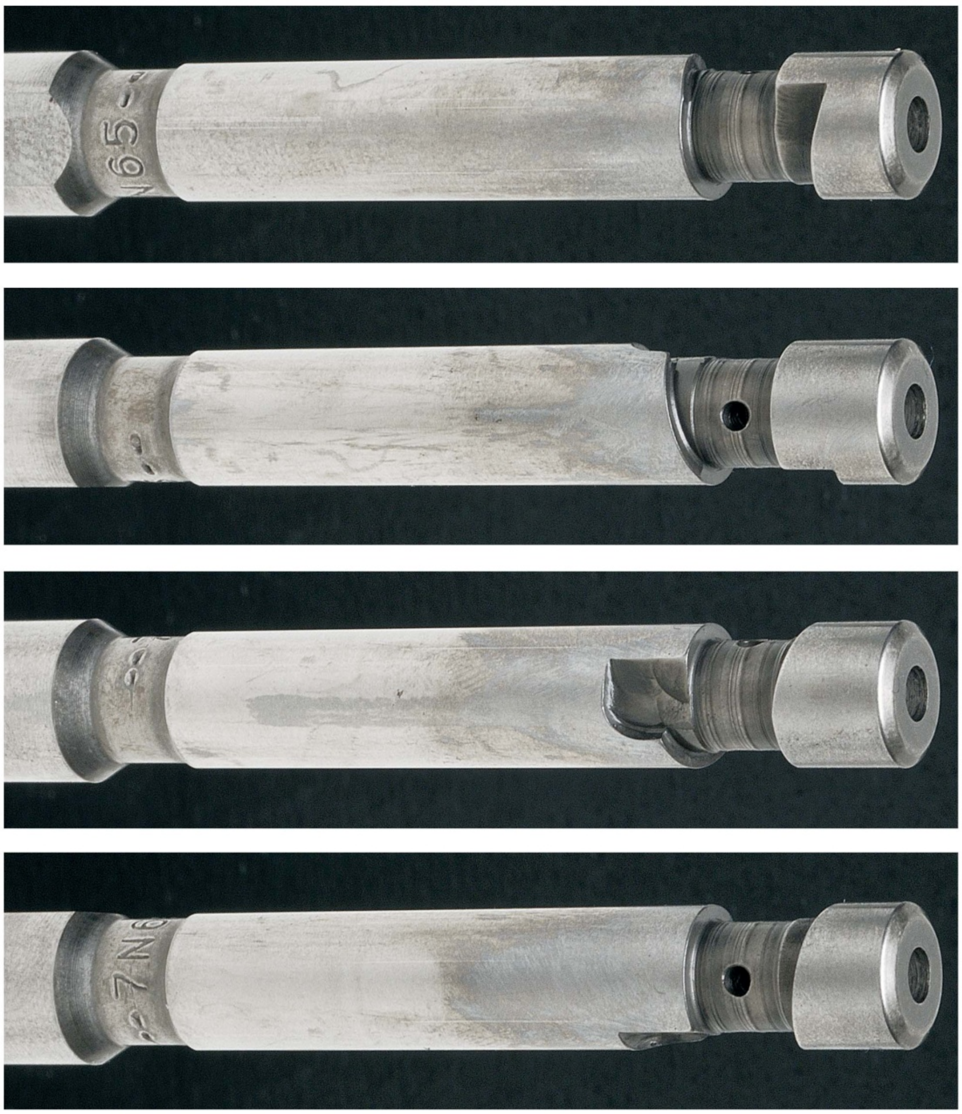

Figure A15. Plunger Condition for Test No. 2 Cylinder 3, F1000/F2000 Fuel at 500 Hours

Table A8. F1000 (S8) Fuel Unit Injector Inspections

Detroit Diesel Fuel Injector Test Results

Injector Model: 7N65
Technician: REG
Injector Location: DDUI02.P4
Test Fuel No.: F1000

Test	Units	Initial Check	Reassembly Test Hours			Test Hours	Test Hours		
Test Hours			0				500		
Injector Valve Opening and Spray Pattern									
Pressure Reference No.			154				132		
Spray Pattern			Good				Good		
Unit Hold Time									
Pressure Drop Time	sec.		273.3				300		
Spray Tip									
Pressure	psig		2000				2000		
Tip Dryness			Dry				Dry		
Needle Travel									
Needle Valve Lift	in.		0.009						
Calibration	ml/1000 strokes		34				34		
Wear	1=light 6=severe		(1-6)	Weight	Wtd		(1-6)	Weight	Wtd
Side 1	(1-6)		1	0.286	0.286		2	0.286	0.572
Side 2	(1-6)		1	0.071	0.071		1	0.071	0.071
Side 3	(1-6)		1	0.214	0.214		1	0.214	0.214
Side 3 Helix	(1-6)		1	0.286	0.286		1	0.286	0.286
Side 4	(1-6)		1	0.143	0.143		1	0.143	0.143
Total	(1-6)				1				1.286

Lubricity

Oil Code:	F1000	Test No.:	DDUI02.P4	Test Hours:	500

Plunger 4

View 1,2,3,4

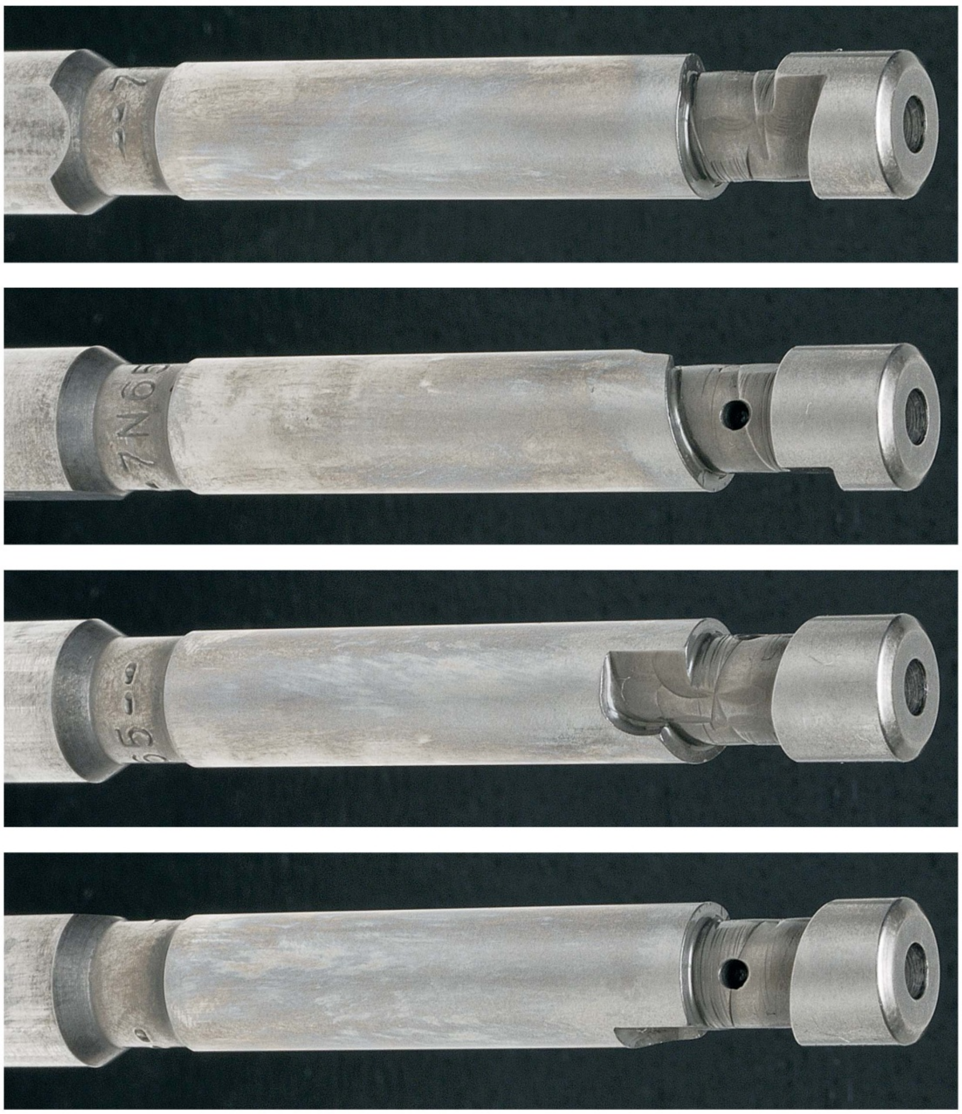

Figure A16. Plunger Condition for Test No. 2 Cylinder 4, F1000 Fuel at 500 Hours

APPENDIX B

Unit Injector Radioactive Tracer Test Study

Unit Injector Radioactive Tracer Tests

A Detroit Diesel 8V-149 injector plunger RAD4 was irradiated by thermal neutrons in the 2PH1 location at the MIT Nuclear Research Laboratory research reactor. The plunger was encased in an aluminum canister packed with graphite wool and purged with helium (He). The average thermal neutron flux of the 2PH1 location is 3.35*10^13 neutrons/cm^2/sec. The test plunger RAD4, along with two small calibration pieces cut from another plunger, were exposed for 4.2 hours.

The irradiated parts appeared to be in as sent condition, with no visible changes to the surfaces. The two calibration pieces were carefully weighed and digested into a liquid solution containing a combination of hydrochloric and nitric acid. The solution was then diluted with DI water into a stock solution volume of 100 ml. A series of four calibrating solution concentrations were made from this stock solution. The calibrating solution concentrations were 1E-6, 1E-7, 1E-8, and 1E-9 gm/ml. These solutions were individually poured into a detector measurement vessel in order of increasing concentration. Each solution was counted on an Ortec High Purity Germanium (HPGe) detector (S/N 45-TP41226A, 80% relative efficiency) with a Canberra DSA-1000 multichannel acquisition system and analyzed with Canberra Genie-2000 gamma spectroscopy software. The measured counts at the 320.1 keV peak (Cr-51) were decay corrected to a reference date of 12/1/2005. Cr-51 has a half-life of 27.7 days. The decay corrected counts were then plotted against concentration and a least squares method was used to determine the slope of the resulting line. This slope is used as the calibration factor to convert decay corrected counts to the concentration of wear debris in the test fuel. The calibration curve is shown in Figure B1.

The Detroit Diesel unit injection rig was charged with the 2000-gram scuffing load fuel and operated with a dummy injector to make sure the system was clean. The rig was de-fueled and a fresh charge of 2000-gram fuel was added and the wear test with the fuel was initiated. The wear test was performed for 33.5 hours, at which time the wear readings with the 2000-g fuel appeared stable and the testing was halted. The system was cleaned and flushed several times due to the difficulties in removing all the tiny wear particles. An undyed on-highway diesel fuel was obtained from the SwRI fleet lab to be used as the good lubricity fuel. The system was charged with the diesel fuel and testing initiated. The unit injector was operated for 32.5 hours at which time the wear readings with the fuel appeared stable and the testing was halted.

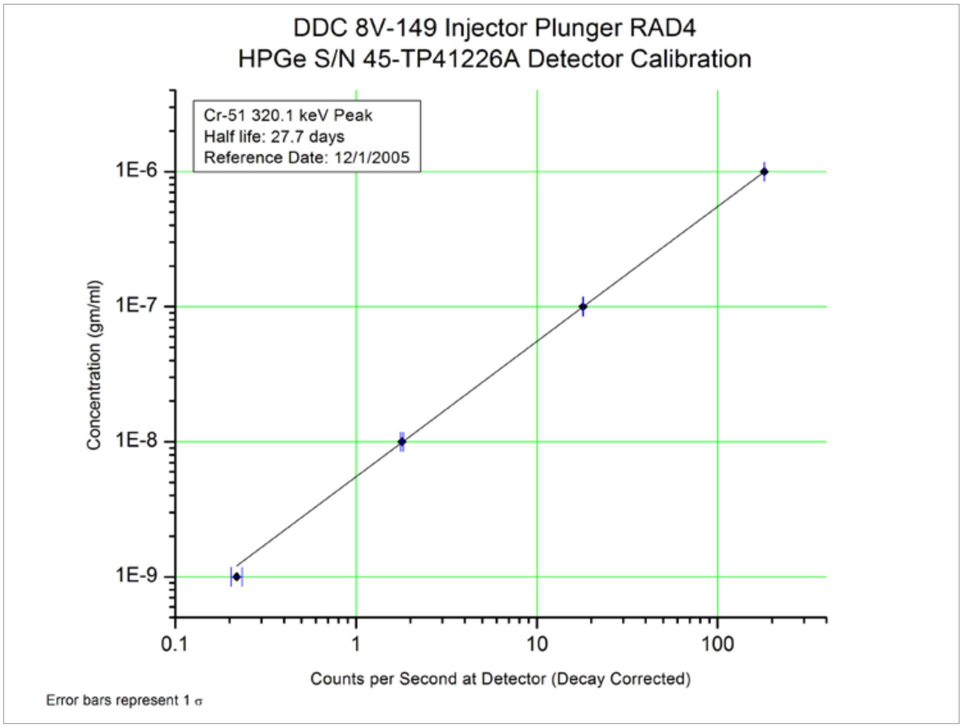

Figure B1. Radioactive Tracer Wear Calibration Curve

Test fuel was circulated through a specially designed stainless steel vessel mounted on an Ortec HPGe detector (S/N 45-TP41226A). The vessel is designed to achieve a good counting efficiency. Fuel flow rate through the vessel was maintained at approximately 1 liter/minute. Sufficient counts were present to allow for a data measurement increment of 30 minutes, allowing for an increased time resolution. The Fuel 2000 was run for 33.5 hours and Fuel 3000 was run for 32.5 hours. Cumulative wear as a function of time is shown in Figure B2. It can be seen that Fuel 2000 had an initially lower wear rate that appeared to increase to a steady state rate starting at approximately 13 hours. Cumulative wear data for this steady state wear region between 13 and 33.5 hours were fitted to a line using the least squares method. This line is shown with 1 standard deviation confidence limits on the plot. The slope of this line represents the steady state wear rate. Fuel 3000 appeared to wear at a steady state rate from the beginning; therefore the entire data set was used to determine the steady state wear rate for Fuel 3000. Steady state wear rates for these two fuels are shown in Table B1.

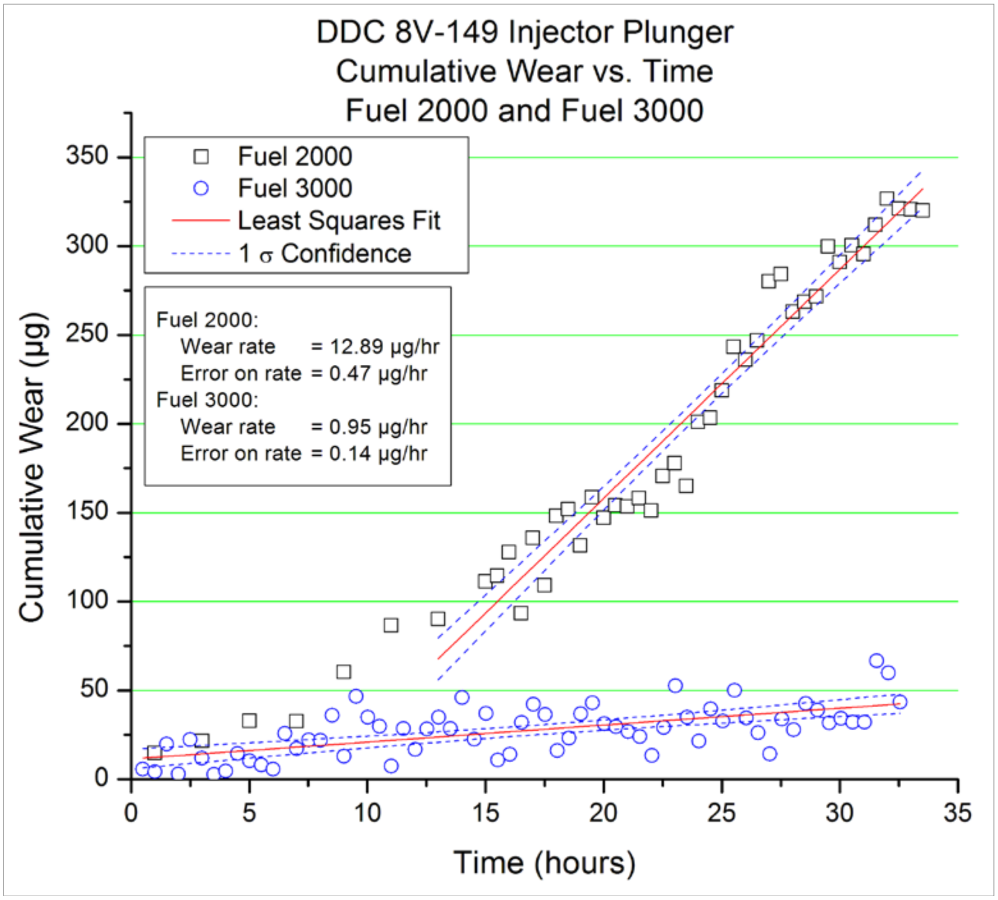

Figure B2. Wear Slopes between Fuels

Table B1. Steady State Wear Rates

Fuel	Wear Rate	Error
2000	12.89 µg/hr	0.47 µg/hr
3000	0.95 µg/hr	0.14 µg/hr

Following removal of the 3000-g fuel the Detroit Diesel unit injector rig was charged with the 1000-g scuffing load fuel. The rig was operated on the 1000-g fuel for 5.3 hours when it seized. The radioactive detection sample time was set at 15 minutes in anticipation of the wear rates being higher than the 2000-g fuel. The number of counts was below a threshold level for the 15 minute samples, so the integrating period was changed to 30 minutes after 3 hours of operation. Even with the 30 minute integration period very small wear rates were observed. Neighboring 15 minute sample counts were added to analyze as 30 minute samples, and the results are plotted as Figure B3. A wear rate is not discernable from the data. It is being suggested that the mechanism for seizure was evident from the beginning, with metal transferred between surfaces occurring, and wear material not showing up as activity in the fuel.

A decayed plunger was reactivated at MIT and the calibrations performed. Wear was checked with Fuel 2000 with the new plunger and revealed a wear rate (10.6 ug/hr) very similar to the wear rate of the first trial with Fuel 2000 (12.9 ug/hr), see Figure B4.

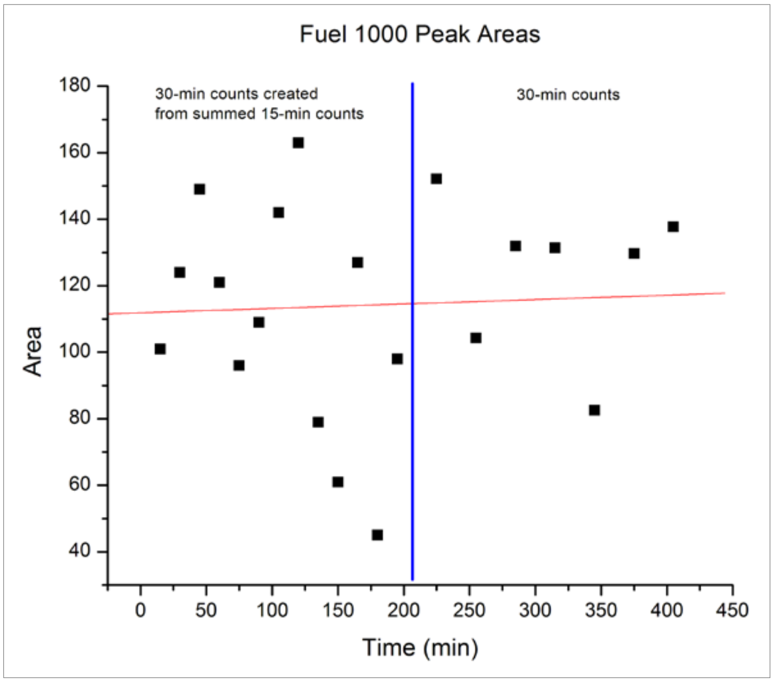

Figure B3. Fuel 1000 Radioactive Data over Test Period

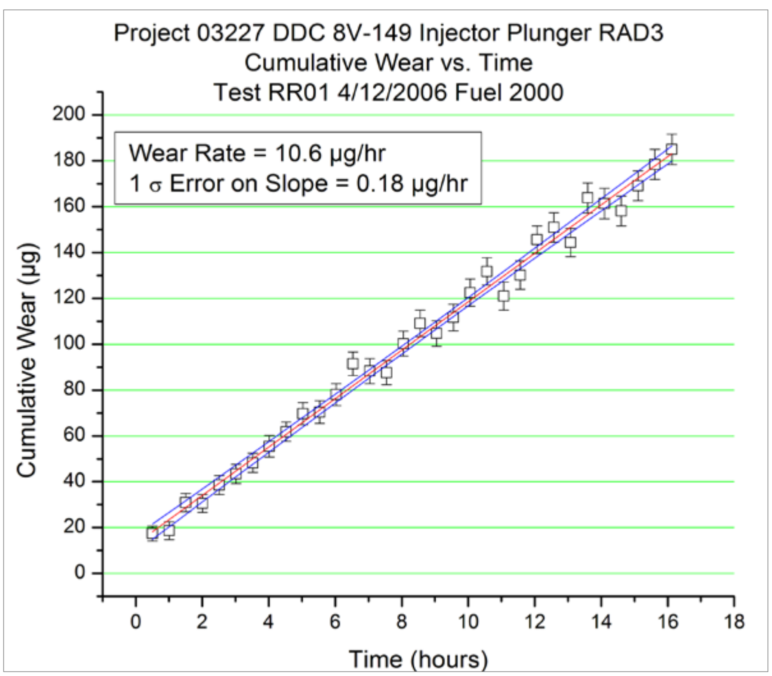

Figure B4. DD 149 Unit Injector Wear with Fuel 2000

The decision was made to add 10 ppm DCI-4A to the Fuel 2000 and look at the wear rate. The initial rate of wear seen (Figure B5) was at a lower level of 7.2 ug/hr before a sudden change in wear occurred. Inspection of the plunger revealed some scoring that might have occurred when the rack was adjusted to match flow rates with earlier work.

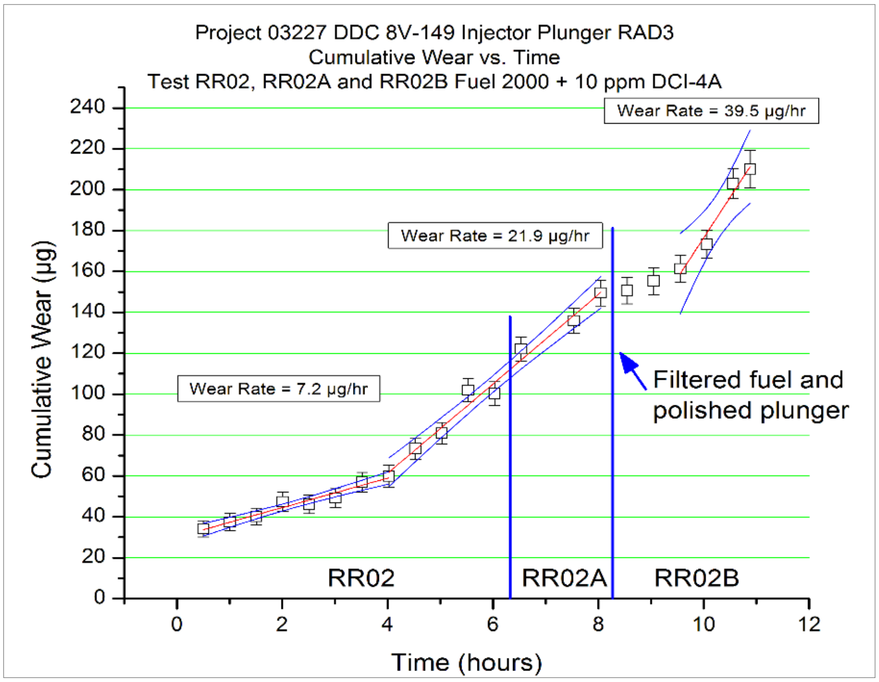

Figure B5. DD 149 Unit Injector Wear with Fuel 2000 + 10 ppm DCI-4A

The unit injector was reassembled and the wear rates check again, after the fuel in the reservoir was run through a clean-up filter. The wear rate was seen to be at an even higher value (39 ug/hr), indicating that the plunger wear was accelerating. The diesel fuel was put into the system to determine if the injector would heal itself when operated with a good lubricity fuel. The wear rate for the diesel fuel is shown in Figure B6, at 24.8 ug/hr. Also in Figure B6 is the wear rate seen when an adjustment was made to center the contact position of the rocker arm on the injector. The rocker arm contact was repositioned when it was noted it was hitting the injector off-center, and it was felt the contact might be adding an additional side thrust to the injector plunger. The realignment did reduce the wear rate, indicating the injector is sensitive to minor variations in alignment and the test method is sensitive enough to detect the result.

The rig had been reconfigured in an attempt to resolve an alignment issue. Initially the wear rate started out low then shifted to a higher wear rate as seen in Figure B7. The cylinder head seemed to start bouncing around on the gasket material (which seals oil from leaking) and the wear rate started going up.

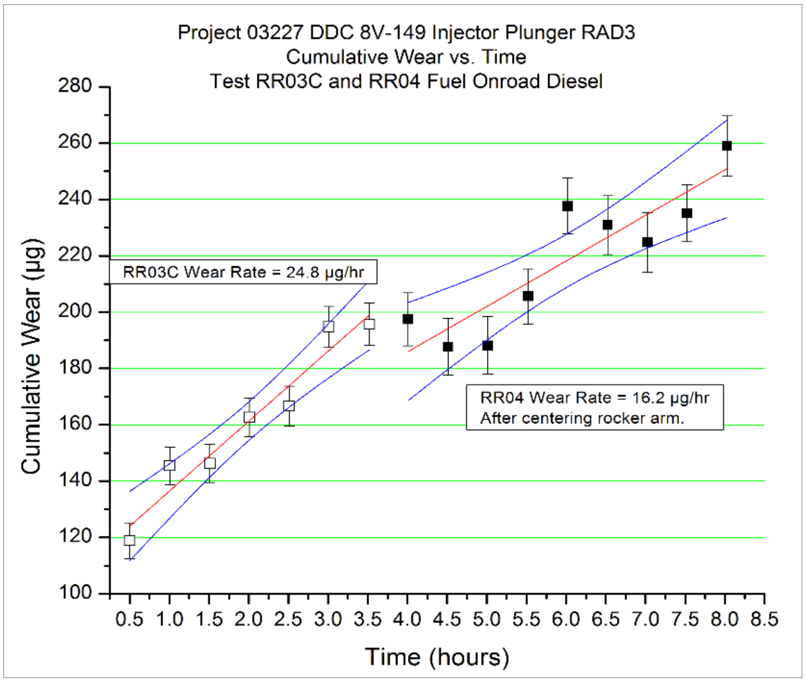

Figure B6. DD 149 Unit Injector with Diesel Fuel and Centered Rocker Arm

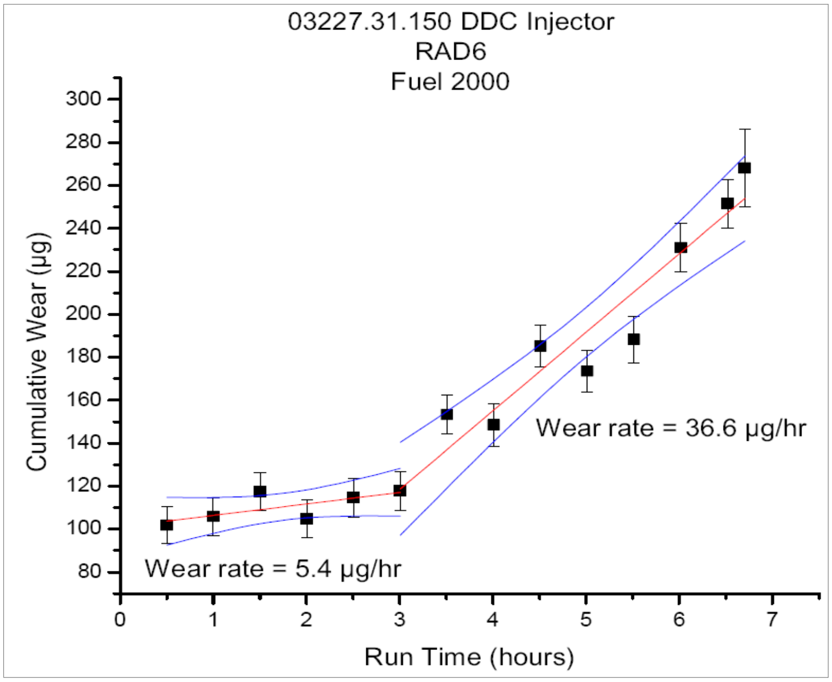

Figure B7. Wear Rate Deviation Attributed to Head Movement

Several experiments were performed with Fuel 2000 to determine adequacy of the injection rig repairs. Prior to operation the barrel and plunger were lapped together in an attempt to polish the surfaces after running misaligned. The plot for Fuel 2000 is shown in Figure B8. The high wear rate eventually decayed to a steady value that repeated day to day, as represented by R603 through R605 in Figure B8. The wear rate stabilized at 62.7 micrograms/hour of material removed from the plunger. During run R606, 9 ppm of corrosion inhibitor fuel additive DCI-4A was added to the fuel, at the time denoted by the dashed vertical line. As seen in Figure B8 the wear rate decreased to a steady value of 27.8 micrograms/hour of material removed from the plunger. This wear rate appeared to stabilize over several days as reflected in runs R606, R607, and R68A. During operation of R68A, a fuel line broke and the test charge leaked out. It should be noted that the data collected was integrated over 30 minutes for the Fuel 2000 runs. At that time it was suggested that Fuel 3000 be put in the system to see the wear results. The Fuel 3000 runs are shown in Figure B9, which reveal an initial high wear rate that eventually stabilizes to a lower value. What is interesting, is the initial wear rate is higher than the rate seen at the end of the Fuel 2000 runs. The system was cleaned between fuels, and flushed with the test fuel until background counts were low, and then filled with the batch of the test fuel. There appears to be a run-in period with a fuel change that is not completely understood. It should be noted the statistics with the lower wear rate, higher lubricity fuel indicate more variability for the 30 minute counting period. More variability is evident because the wear rate is lower and also because the activity of the isotope being monitored is decaying.

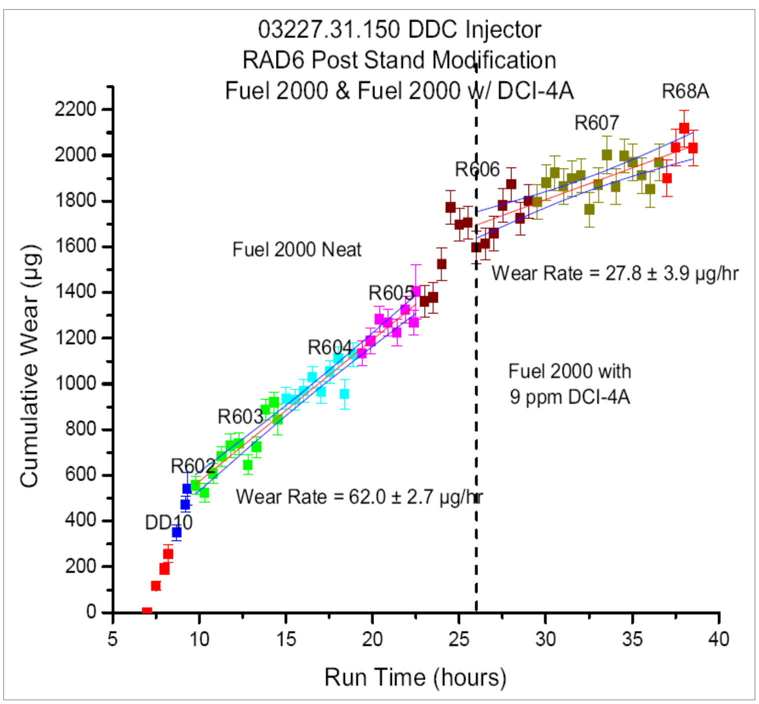

Figure B8. Fuel 2000 and Fuel 2000 + DCI4A DDC Unit Injector Wear Rates

The data from the unit injector using radioactive tracer directionally showed wear between fuels, but was too inconsistent, and did not repeat within a fuel. Furthermore the decay of the isotope for the test plunger approached a level that required a new activation to complete the test program. Inspection of the plunger revealed it to be worn, and would not be suitable for reactivation. Activating a new plunger would mean repeating some test fuels, again. It was decided the RATT approach was not working with the current test rig, partly due to the rig not being robust enough.

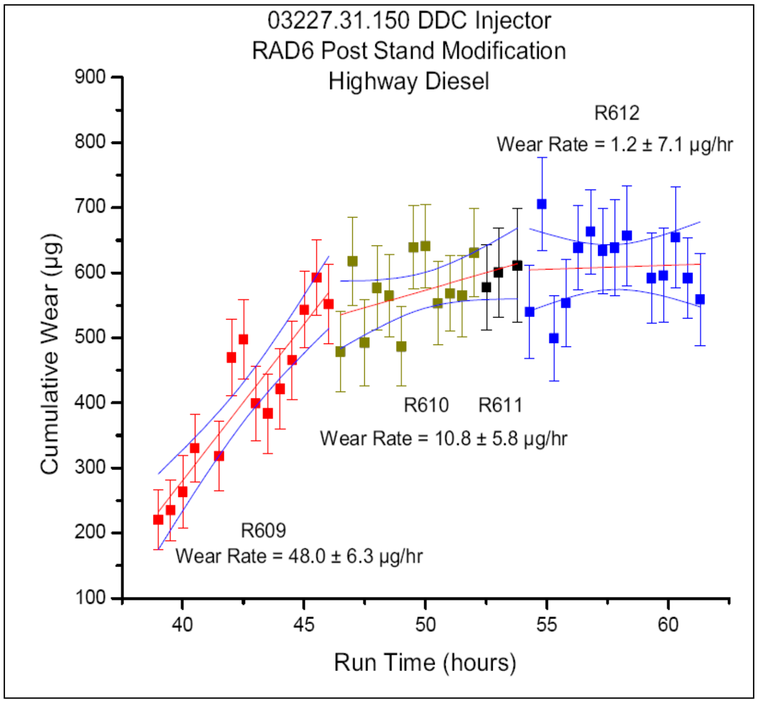

Figure B9. Fuel 3000 DDC Unit Injector Wear Rates